DOCTOR OF PHILOSOPHY

Flandrian relative sea-level changes in the Cree estuary region, south west Scotland

Wells, James Michael

Award date:
1997

Awarding institution:
Coventry University

Flandrian relative sea-level changes in the Cree estuary region, south west Scotland

by

James Michael Wells

Thesis submitted in partial fulfilment of the University's requirement for the degree of Doctor of Philosophy.

1997

Coventry University

Dedication

This thesis is dedicated to Stan (1909-1996), Ena, Ron, Anne, Bridget and Charlie (1983-1997) with love.

Acknowledgements

The author will remain eternally grateful to Prof D. E. Smith, Dr A. G. Dawson, and Dr T. Mighall for providing the opportunity to undertake this research. Their advice, support, encouragement and friendship shown throughout the duration of this project has been much appreciated. Without a doubt the exchange of ideas and discussion of Scottish malt whiskies has certainly proved invaluable.

Funding for this research and all radiocarbon dates was provided by the European Union contract (EV5V-CT930266) *Relative Sea-level Changes and Extreme Flooding Events Around European Coasts* and the Centre for Quaternary Research (Coventry University). The author is grateful to Shirley Addleton, Elly Bruetschy, Jim Campbell, Adrian Coles, Dr R. Cullingford, Sue Dawson, Lorne Elliott, Pete Golightly, Lee James, Dr R. Jones, Jason Jordan, Dr S. Shi, Mr Steven Turnbull from Doncaster and Liz Turner for assistance in the field and in the laboratory. Both Chris Gleed-Owen (mollusc analysis) and Lucy Holloway (particle size analysis) deserve particular praise for providing freely their expertise and time. Thanks are also due to the numerous landowners in Dumfries and Galloway for providing access to their land. Instruction in microfaunal identification was kindly given by Dr A. M. Wood (marine ostracods), Dr H. I. Griffiths (freshwater ostracods), Rob Hindson (foraminifera) and Prof J. R. Haynes (foraminifera). Many thanks are extended to Dr S. Haslett, Dr S. Harrison, Dr D. H. Keen, Prof J. D. Peacock, Dr Ian Shennan and Dr W. Westerhoff all of whom have provided good advice and critical discussion.

To all those that have put up with me in Coventry over the last four years - in particular Steve, Sandar, Karen, Emma, Suz, Bernard, Rosie and Jack - unlucky, at least its over now. Finally the author can not thank enough the immeasurable support, encouragement and friendship shown by Anne de la Vega, Lorne Elliott, Katherine Selby and Adrian Wood.

Abstract

The northern shoreline of the Solway Firth (SW Scotland) is well established as being a region containing a wealth of evidence for changing sea-levels since the end of the last glaciation *circa* 10,000 years ago (see Jardine, 1975). The aim of this thesis is to reconstruct Flandrian relative sea level changes in the Cree estuary region, in the western Solway Firth.

Geomorphological, lithostratigraphical and biostratigraphical investigations (including foraminifera, ostracod, mollusc, pollen, diatom, charcoal and particle size analyses) from three contrasting coastal environments are undertaken. In the valley of the Cree estuary (NX 44 60) an extensive and deep sequence of Flandrian estuarine muds intercalated with terrestrial peats are recorded. This contrasts with a very different sedimentary sequence at the small coastal embayment of Brighouse Bay (NX 63 45). Here the relative sea-level story is complicated by the existence of a fossil barrier underlying a dune system behind which are marls that contain a marine micro- and macro-fauna. Further to the east at West Preston (NX 95 55) this open coastal location provides evidence for late Flandrian relative sea-level regression.

Relative sea-level index points are determined using radiocarbon dating on critical marine/freshwater boundaries to provide a chronological framework. These have been used to construct an age-altitude graph which charts the changes in relative sea level throughout the Flandrian for the Cree estuary region.

In summary the results show a relative sea-level sometime in the Late Devensian (*circa* 13,000 to 11,000 ^{14}C years BP) above approximately 0m O.D. after which relative sea-level must have fallen to an unknown minimum. Following deglaciation at the end of the Younger Dryas/Loch Lomond Stadial relative sea level rose to a maximum of *circa* 0m O.D. (approximating here to a former M^1 level - i.e. the mid-point of Highest Astronomical Tide and Mean High Water of Spring Tides) before regression at *circa* 8,500 ^{14}C years BP. The rapidly rising seas of the Main Postglacial Transgression are recorded approximately after this date to a culmination at *circa* 9m O.D. between 6,800 and 6,200 ^{14}C years BP. Two subtle relative sea level oscillations followed between 5,800 and 5,000 ^{14}C years BP and 4,500 and 3,700 ^{14}C years BP depositing sediments to a maximum of *circa* 10m O.D. prior to a relative sea-level fall to *circa* 5m O.D. by *circa* 1,800 ^{14}C years BP. Since this time relative sea level is assumed to have fallen steadily to present levels with M^1 calculated for the Cree estuary region at *circa* 4.35m O.D.

Through the comparison of the results from the Cree estuary region with elsewhere in the Solway Firth and the northern British Isles it is believed that a number of the relative sea-level change characteristics can be identified elsewhere. Of particular note is that the Main Postglacial Shoreline in areas toward the periphery of isostatic uplift may not be the highest Flandrian shoreline feature.

Contents

List of figures

List of tables

Chapter 1 Introduction

1.1 Introduction

This project examines and interprets morphological, lithostratigraphical and biosratigraphical evidence for Flandrian (see Hyvärinen, 1978) relative sea-level changes in the Cree estuary and Wigtown Bay region on the northern side of the Solway Firth, SW Scotland. Glacio-isostatic uplift and changing sea surface levels around the coastline of Scotland during the Late Devensian and Flandrian have resulted in a complex sequence of marine transgression and regression (e.g Sissons *et al.*, 1966). With the concept of global eustasy rejected (Morner, 1976) it has become necessary for studies to be undertaken on a regional scale to establish relative sea-level changes in order to reduce the effects of tidal inequalities, earth movements and variations in the geoid configuration (Haggart, 1982). The advantages of estuaries for such research, where a low energy environment is conducive to the deposition and preservation of intercalated marine and terrestrial sediments, is well known (Godwin, 1956). The coastline of the Solway Firth, comprised of a number of such estuaries, is an ideal region for such a study.

In contrast to most other similar studies the Solway shoreline has already been the focus for much research of former sea levels (e.g. Jardine, 1964, 1967, 1971, 1975, 1977, 1980; Walker, 1966; Nichols, 1967). With the large areas of raised marine deposits along the shores of the estuary such as those underlying the Moss of Cree, Lochar Moss and Wedholme Flow this attention is not undeserved. Jardine's research (*op cit.*) involving morphological mapping, stratigraphical determination and radiocarbon dating established the potential of the region for sea level studies. Following the identification of different patterns of sea level change along the length of the northern shore of the Solway estuary the evidence was used to form two separate sea level curves - one for the head of Wigtown Bay and the other for eastern Solway Firth (Jardine,1975 see Figures 10 and 11). This work has been valuable for the understanding of relative sea-level change on the northern shore of the Solway Firth, but some of the evidence that supports the two aforementioned sea-level curves has been subject to a number of criticisms:

> *'In the Solway Firth area....[sea-level] index points are largely unsupported by pollen or other micropalaeontological techniques which could be used as a check on dating, as an aid to the identification of possible breaks in sedimentation over lithological boundaries and to aid assessment of the direction of environmental change. In consequence the curves produced have few limits placed on the direction of sea-level movement save for the original or derived altitude and age of the index points.'* (Haggart, 1989 p.76)

It is from these areas that the present study will develop an account of relative sea-level change and differential land surface uplift due to isostatic rebound, whilst at the same time bringing the research methodologies in line with comparable studies (e.g. Tooley, 1978; Haggart, 1982; Smith *et al.*, 1992, Dawson and Smith, 1997). In addition it is intended that the thick fine-grained sediments that comprise the fossil estuarine deposits that flank the Cree Estuary are characterised using microfossil analysis in order to identify the changing nature of the environment of deposition. In this way it is hoped that an insight into the evolution of the Cree estuary can be achieved and related to rates of relative sea-level change.

1.2 Overall aim of study

To establish the pattern and extent of Flandrian relative sea-level movements for the Cree estuary region, SW Scotland.

1.3 Objectives

The objectives of the project are as follows:

- to determine the pattern of relative sea-level changes in the Cree estuary region using morphological mapping, litho- and bio-stratigraphical studies

- to develop the potential of foraminifera and ostracod analyses in studies of relative sea-level change

- to establish the depositional environment of the marine and estuarine sediments of the Cree estuary region using micropalaeontological analysis

- to establish an absolute chronology for those periods of positive and/or negative tendencies in relative sea-level in the Cree estuary region

- to construct an age-altitude relative sea-level graph for the Cree estuary region

- to utilise the model of relative sea-level change in the Cree estuary region as an analogue for a re-evaluation of the previously published (Jardine, 1975; 1980) relative sea-level data for the eastern Solway Firth

- to compare and contrast the pattern of relative sea-level change in the Cree estuary region with similar studies elsewhere in the northern British Isles

1.4 The study area

The potential of the Solway Firth for studies of Flandrian relative sea level changes has already been established and some suitable sites for such investigations have been identified (e.g. Nichols, 1967; Jardine, 1975). This study has therefore aimed to return to a number of those sites as well as identifying other suitable locations. The main study area (Figure 1.1) includes the raised fossil estuarine sediments that flank the Cree estuary at the head of Wigtown Bay and which are overlain by large tracts of peat.

A further site for investigation has been identified at the small inlet of Brighouse Bay (Figure 2.6) where a sandy beach is backed by stabilised sand dunes. The contrasting nature and size of this location to the Cree estuary provides an ideal opportunity to compare the records of relative sea-level preserved at two very different but geographically close sites. In this study the term "Cree estuary region" is taken to include Brighouse Bay. In addition the previously investigated location of West Preston (Jardine, 1975) is returned to in order to provide detail for late Flandrian relative sea-level changes (Figure 2.6).

1.5 Form of the thesis

Chapter 2 summarises the present state of the science of relative changes of sea level in Scotland. This includes a brief review of Late Devensian glaciation/deglaciation and outlines the implications that it has for coastal evolution throughout both this time and for the subsequent Flandrian. The results from research already undertaken into Late Devensian and Flandrian sea level changes, particularly around the coast of Scotland, can elucidate further the pattern and impact of crustal movements on coastal evolution. This includes a detailed review of relative sea-level change studies on the northern shoreline of the Solway Firth.

Chapter 3 outlines the methods and techniques used in the current investigation. The palaeoecological techniques of pollen and diatom analysis that are both most commonly used in studies of relative sea-level changes are reviewed. In this study, however, the micropalaeontological techniques of foraminifera and ostracod analyses has been applied extensively to further elucidate patterns of relative sea-level changes. To date these two techniques have been rarely utilised in similar studies in the British

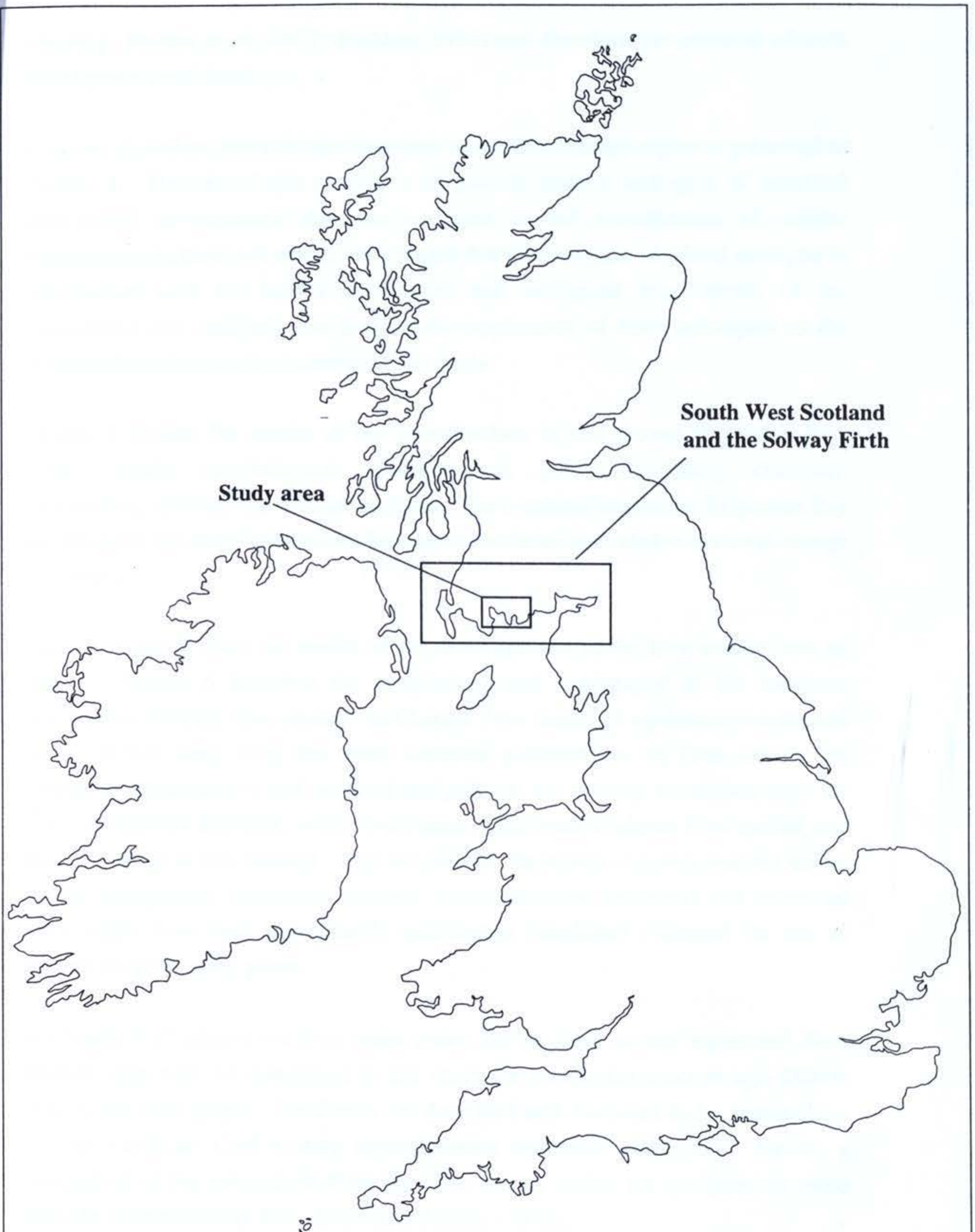


Figure 1.1 Location map of South West Scotland, the Solway Firth and the study area.

Isles (e.g. Haynes *et al.*, 1977; Huddart, 1992) and therefore the potential of both techniques is considered.

A survey of modern intertidal environments in the Cree estuary region is presented in Chapter 4. The aim of this chapter is to provide modern analogues of intertidal depositional environments that can be used to aid identification of similar environments in the fossil record. It is hoped that the provision of a local analogue in combination with the known distribution and ecological requirements of the foraminifera and ostracods can develop the application of both techniques to the problem of relative sea-level change in this study.

Chapter 5 records the results of the investigations in and around Brighouse Bay. These include morphological, stratigraphical, pollen (including charcoal), foraminifera, ostracod and mollusc analyses. The combined results for Brighouse Bay are discussed and their implications for coastal evolution and relative sea-level change considered.

Chapters 6 and 7 detail the results of the investigations in the Cree estuary and its valley. Chapter 6 describes the morphology and stratigraphy of the locations investigated from the Cree estuary. In Chapter 7 the results of a palaeoenvironmental survey of five cores from the raised estuarine sediments in the Cree estuary are presented. Foraminifera and ostracod analyses are the primary techniques used for this investigation although, where undertaken, additional evidence from pollen and diatom analysis is also detailed. Also detailed are the results of pollen analysis across critical stratigraphic boundaries between marine/estuarine sediments and terrestrial peats which have been subsequently radiocarbon dated and evaluated for use as relative sea level index points.

In Chapter 8 all relative sea level index points for the Cree estuary region and West Preston (Appendix A) determined in this study are used to construct an age-altitude relative sea level graph. The results are described and discussed and a terminology for the Flandrian Cree estuary region marine sediments suggested. Finally a comparison of the new results from the Cree estuary region are compared to those from the eastern Solway Firth detailed by Jardine (1975).

In Chapter 9 the relative sea-level evidence from this study is compared and contrasted with other similar studies from the northern British Isles. In addition the results are placed within the context of global sea-level change since the collapse of the Late Devensian ice sheets.

Chapter 10 summarises the main conclusions of this investigation and establishes the degree of success in achieving the aims and objectives of the project (as outlined above). The use of foraminifera and ostracod analyses in studies of relative sea-level change are considered. Finally, the potential for future work on relative sea-level change and coastal evolution in the Solway Firth region is outlined.

Chapter 2 Literature review

2.1 Introduction

Jamieson (1865) introduced the principle of isostatic theory to explain the relative changes of sea level that he had identified around the coastline of Scotland. He recognised that the land uplift required to form raised shoreline features could result from crustal recovery following unloading of ice from the earth's crust. Later Wright (1911, 1937) elaborated this theory to incorporate the interaction of variable sea-level change and land movement following deglaciation. Termed the Isokinetic Theory it maintains that the interaction of these two movements are responsible for raised shorelines in areas subject to glacio-isostatic uplift. The result of this process is that raised marine features that were formed at the culmination of the same marine transgressive event are progressively lower in altitude and younger in age with increasing distance from the centre of isostatic recovery (see section 2.3.1).

More recently the complex nature of the relationship between sea surface and land movements in areas subject to glacio-isostasy has been considered in greater detail (Mörner, 1980). Sea surface changes can result from a number of factors including water volume changes, changes in the shape of the equipotential surface of the geoid and changes in the shape of the ocean basins (Figure 2.1; Fairbridge, 1983). Isostatic patterns reflect the effects of ice loading (glacio-isostasy), water loading (hydro-isostasy) and sediment loading (sediment-isostasy). Global factors include geoidal eustasy (Gaposchkin, 1973) while local factors include consolidation of sediments (Haggart, 1982).

The first part of this review outlines evidence for the last ice sheet to have affected Scotland and includes a consideration of the influence of this ice sheet on isostatic movements and the relationship of these movements to sea-surface changes during this time period. The second section presents a summary of Flandrian shoreline investigations around the coast of Scotland. This section includes a more detailed account of the current state of relative sea-level studies in the northern Solway Firth region. For locations of all place names mentioned in the text see Figures 2.2 and 2.6.

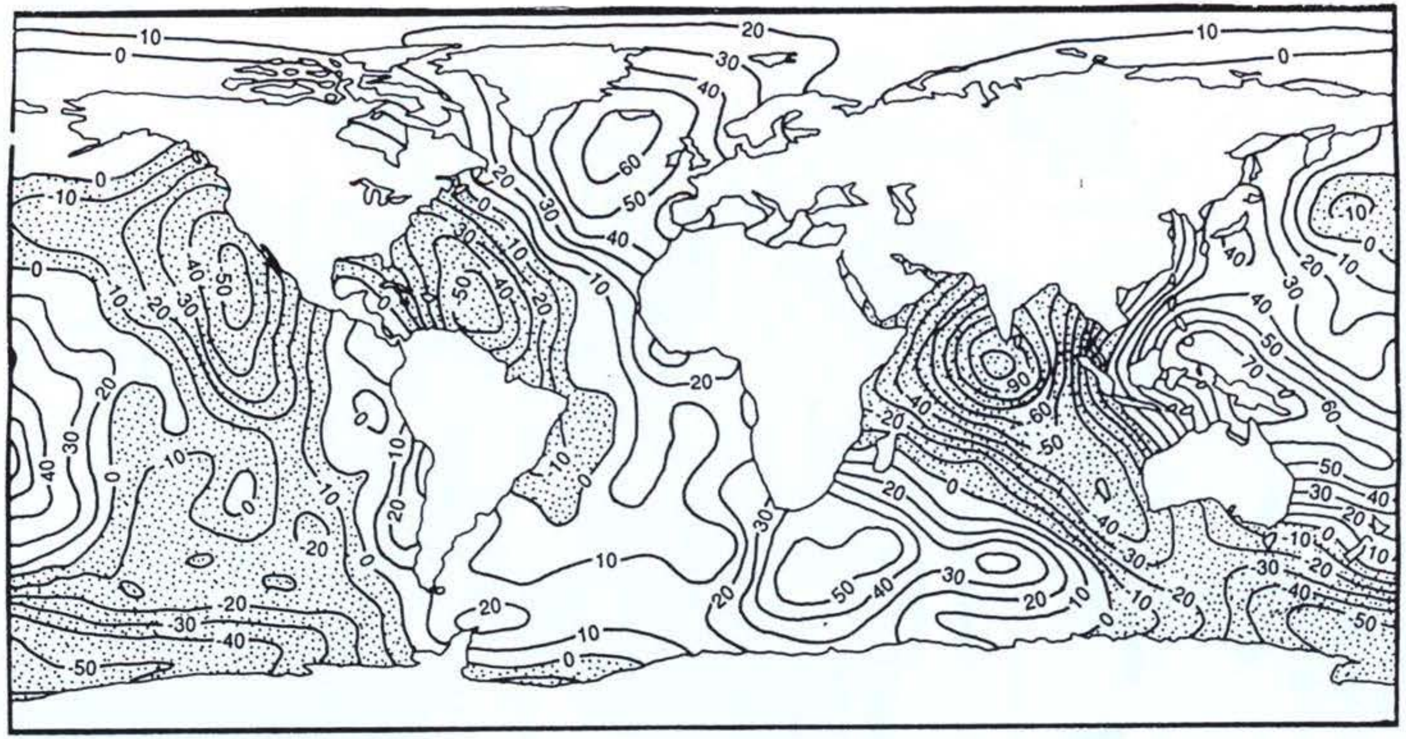


Figure 2.1 Global geoid map in metres with respect to the best-fitting ellipsoid (after Van de Plassche). Negative areas are shown shaded

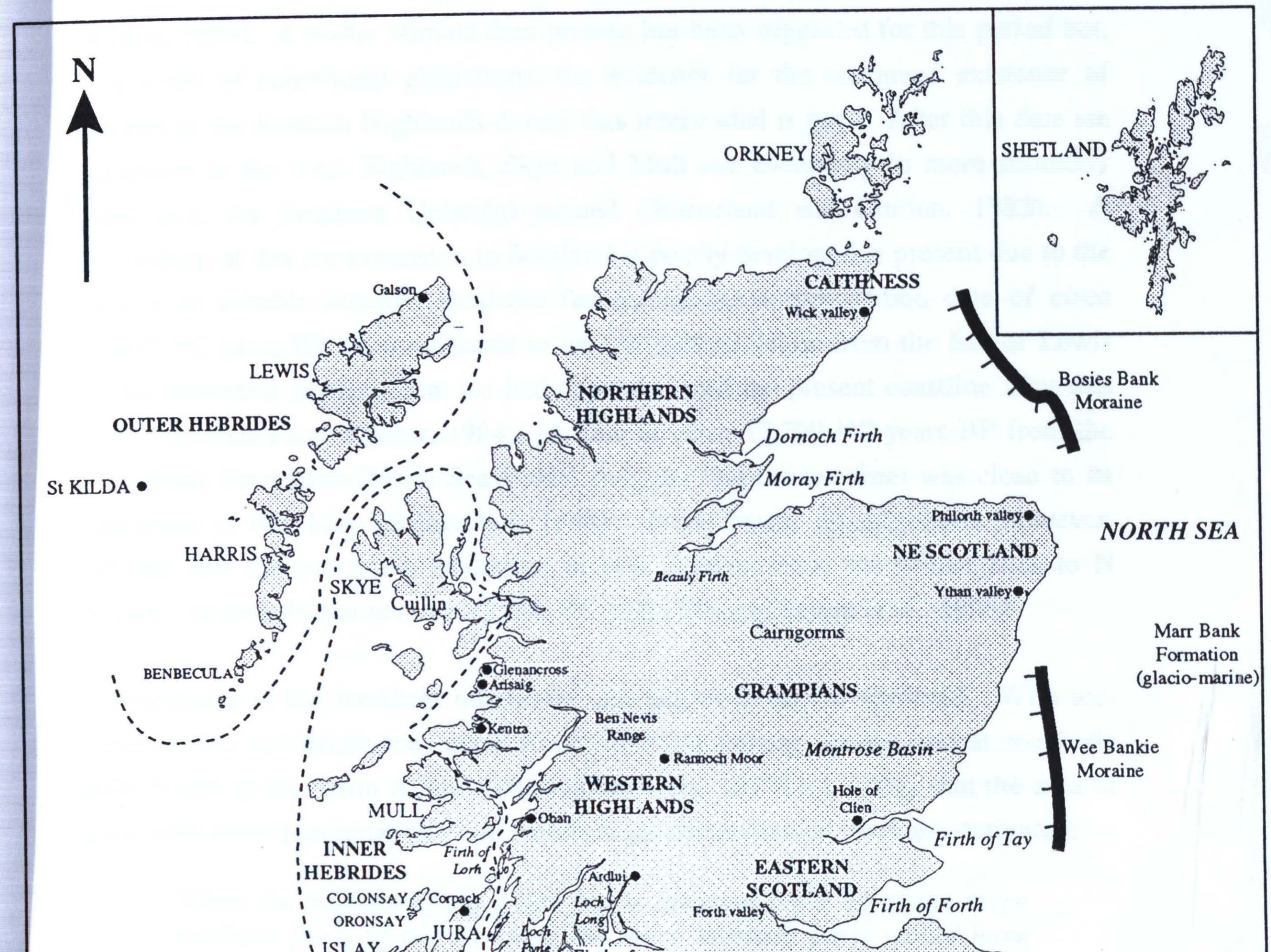


Figure 2.2 Location of sites and areas described for Scotland (for detail of SW Scotland see Figure 2.6)

2.2 The Lateglacial in Scotland

2.2.1 Late Devensian Glaciation

Middle Devensian interstadial deposits suggest that lowland and coastal areas of Scotland were ice-free between *circa* 35,000-26,000 ^{14}C years BP (Sutherland and Gordon, 1993). A cooler climate than present has been suggested for this period but, as a result of subsequent glaciations, the evidence for the continued existence of glaciers in the Scottish Highlands during this interstadial is poor. After this date ice expansion in the west Highlands, Skye and Mull and eventually in more southerly areas (e.g. the Southern Uplands) ensued (Sutherland and Gordon, 1983). A chronology of this ice expansion in Scotland is poorly developed at present due to the paucity of suitable deposits available for dating, but a radiocarbon date of *circa* 23,000 ^{14}C years BP from molluscs in ice-transported debris from the Isle of Lewis (Outer Hebrides) suggests that ice had expanded past the present coastline after this date (Sutherland and Walker, 1984). A date of *circa* 17,700 ^{14}C years BP from the Marr Bank Formation (North Sea Basin) suggests that the ice sheet was close to its maximum at this time (Sutherland, 1984). Some recent investigations, however, indicate that the maximum glaciation in NW Europe, from the British Isles to N Norway, occurred prior to *circa* 22,000 ^{14}C years BP (e.g. Sejrup *et al.*, 1994).

Synchroneity of the ice-sheet maximum can not, however, be assumed. With ice-sheet growth and decay considered to be linked to shifting oceanic and atmospheric polar fronts in the North Atlantic (Ruddiman *et al.*, 1977) it is likely that the area of maximum snow precipitation - and therefore ice accumulation - was not stationary:

> '*When the position of the polar fronts favoured build up of the more southern parts of the ice-sheet the more northern parts would have been less favoured and the ice margin here may have been retreating.*' (Sissons, 1981; p.11)

It has further been suggested that the northward shift of the oceanic and atmospheric polar fronts prior to the Late Devensian interstadial may have reinvigorated ice sheet growth due to increased precipitation over Scotland resulting in the Wester Ross Readvance (Robinson and Ballantyne, 1979).

The distribution and thickness of the Late Devensian mainland ice sheet has been the focus of much speculative discussion (e.g. Boulton *et al.*, 1977, 1985). Previous researchers have suggested that the mainland ice covered most or all of the mainland including the Outer Hebrides, with Shetland being overwhelmed by the Scandinavian ice sheet which also deflected Scottish ice across Caithness and Orkney (Sissons, 1981), thus implying that the Scandinavian and British ice sheets were confluent

(West, 1972; Boulton *et al.*, 1977; Denton & Hughes, 1981). In addition the interpretation of end moraine features of Late Devensian age off the east coast of Scotland (e.g. Wee Bankie Moraine; Bosies Bank Moraine) indicates an ice free corridor between the Scottish and Scandinavian ice sheets during the Late Devensian (Sutherland, 1984; Stoker *et al.*, 1985), a view supported by subsequent investigations (Cameron *et al.*, 1987; Serjup *et al.*, 1987; Hall and Bent, 1990).

Off the west coast of Scotland the Late Devensian ice sheet has been suggested as terminating north of Lewis (Sutherland, 1991) but with a larger ice lobe extending west of the Hebridean Islands toward the shelf edge (Selby, 1989; Peacock *et al.*, 1992). Striae and erratic evidence suggest the development of a local ice centre in the Outer Hebrides with a maximum ice thickness of about 400 m (e.g. Peacock, 1980, 1991) as well as an unglaciated area in north west Lewis (Sutherland and Walker, 1984). Thin diamicts that occur at Galson, north west Lewis, have been interpreted as glacial deposits indicating that there was complete glaciation of this area during the Late Devensian (Hall, 1995). Ballantyne and McCarroll (1995) concur with this interpretation suggesting an independent ice dome on the Outer Hebrides (maximum altitude *circa* 700 m) whose margin reached *circa* 7-10 km WNW of the present coastline of North Harris.

Unglaciated areas during the Late Devensian glaciation may have existed in NE Scotland (Hall 1984), Caithness and Orkney (Synge, 1977). Striae and erratics supporting a deflection of the Scottish ice by Scandinavian ice probably relate to an earlier glaciation (Sissons, 1981). Some, however, argue for complete glaciation in these areas at this time (Hall and Whittington, 1989; Hall and Bent, 1990).

Striae and erratics from the Ben Nevis range reach 1100m (Sissons, 1967; Thorp, 1987). Similarly in the Southern Uplands (notably on The Merrick) erratics indicate overtopping of the mountains (Cornish, 1981). In the Northern Highlands periglacial landforms of Late Devensian age on mountain summits at *circa* 700-800m O.D. indicate the former existence of nunataks (Ballantyne *et al.*, 1987) as do similar features on the tops of the mountains of the Trotternish Peninnsula, Isle of Skye, implying local ice thicknesses ranging from *circa* 450-600 m O.D. (Ballantyne, 1990). Numerical modeling of the main Highland ice mass, based partly on the trim-line data of Ballantyne *et al.* (1987), further supports the contention that the Late Devensian ice sheet was not particularly thick (Lambeck, 1991a, 1991b). The evidence, therefore, suggests that the separate low level ice domes that formed over Scotland during the Late Devensian (e.g Southern Uplands, Cuillin, Mull, Outer Hebrides, Cairngorms and South East Grampians) influenced considerably the pattern and extent of regional glaciation.

Evidence from early isobase models of the Main Postglacial Shoreline indicated Rannoch Moor as the centre of isostatic uplift (Sissons, 1967). With increasing data, later isobase maps reveal a possible northward shift of this centre of recovery during the Flandrian (see section 2.3.1; e.g. Firth *et al.*, 1993) suggesting that depression of the crust during the Late Devensian and subsequent isostatic recovery might have been more complex than previously thought.

The distribution of erratics in the Southern Uplands indicates clearly that there was a centre of ice accumulation in this region during the Late Devensian maximum (Sissons, 1967). From this evidence it has been possible to reconstruct ice flow patterns (Figure 2.3) that show that Southern Uplands ice encroached northwards into the Central Lowlands (Sissons, 1967). In addition Gray (1995) has proposed that the Southern Upland ice dome was prominent enough to have influenced uplift patterns for the region. This is further supported by post-glacial shoreline uplift patterns (Haggart, 1988).

Minimal sea levels in the North Sea during the maximum of the Late Devensian ice sheet were considerably lower (*circa* -110m) than at present (Jansen, 1976). The presence of a rock platform off the coast of St. Kilda off the west coast of Scotland has similarly been recorded at *circa* 120m below present sea levels (Sutherland, 1984). Isostatic effects on the land have, however, resulted in variable relative sea-levels being recorded around the coastline of Scotland at this time. For example, along the west coast of Scotland and on the Inner Hebrides numerous high rock shoreline fragments (maximum of *circa* 40m) have been interpreted as being of Late Devensian age and would indicate high relative sea levels around the ice margin at this time (see Dawson, 1984). Away from the centre of ice sheet dispersal such as on St. Kilda, Orkney, Shetland and the Outer Hebrides unglaciated raised rock platforms are, however, absent (Sissons, 1983).

2.2.2 Regional deglaciation

It remains uncertain whether there was total or only partial deglaciation of the Late Devensian ice sheet in the British Isles prior to the last lateglacial interstadial (Sissons 1974, 1981, 1982). The northward shift of the oceanic polar front to the north of Scotland (Ruddiman and McIntyre, 1973) allowing temperate Atlantic waters to reach the Scottish coast (Peacock and Harkness, 1990) is considered to have resulted in a rise of marine and atmospheric temperatures close to present day values by approximately 13,000 ^{14}C years BP (Bishop and Coope, 1977; Atkinson *et al.*, 1987). However, this shift was not considered to have been the cause of ice sheet decay with deglaciation taking place mainly at a time when polar waters are thought to have surrounded Britain (see 'Errol beds' discussed below). Precipitation starvation rather than increasing temperatures was probably the main factor in ice sheet stagnation (Lowe & Walker, 1984). Radiocarbon dates on organic sediments at locations close to the probable centre of the Late Devensian ice sheet indicate a minimum date for deglaciation from most (if not all) of Scotland of about 13,000 ^{14}C years BP (see Sissons & Walker, 1974). In the Southern Uplands a date of 12,940±250 ^{14}C years BP provides a limiting date for deglaciation in this area (Bishop, 1963). Cold climate Late glacial marine deposits in the Stranraer area have been used to imply that deglaciation of the north-western portion of the Irish Sea pre-dates deglaciation in the Firth of Clyde (Sutherland, 1984). The absence of corresponding sediments east of Stranraer along the Solway coastline may indicate prolonged ice cover in this region (see section 2.4.1). If accepted then the above evidence may support the Perth Readvance ice limits of Sissons (1967) in this region.

Despite the indication of high early interstadial temperatures, coleopteran, pollen and faunal reconstructions all suggest that much of the period between 13,000-11,000 ^{14}C years BP was dominated by a temperature *circa* 2-3 ^{o}C cooler than present (Sutherland and Gordon, 1993). This trend of falling temperatures throughout the interstadial in Britain has been confirmed more recently using coleoptera analysis in combination with detailed AMS radiocarbon dating (Lowe *et al.*, 1995). The evidence from Gransmoor (East Yorkshire) shows initially high (*circa* 20°C) inferred mean July temperatures at approximately 13,000 ^{14}C years BP before falling steadily to *circa* 10°C by the commencement of the Loch Lomond Stadial. These data have also been correlated with dates for the Greenland ice sheet cores and reveals a strong relationship between falling temperatures and a reduction in ice accumulation rates. Lowe *et al.* (1995) conclude that although climate fluctuations in Britain may have just preceded those in Greenland, the major climate changes that occurred in the two regions at the last glacial-interglacial transition appear to have been broadly in phase.

They also suggested that a measure of synchroneity is implied between atmospheric circulation changes over Greenland and parts of northwest Europe during the last glacial-interglacial transition which, in turn, supports the suggestion that major warming episodes in the North Atlantic region were characterised by marked storm-track displacement northwards towards Iceland (see Kapsner *et al.*, 1995).

For SW Scotland mean July air temperatures at the commencement of the interstadial have been estimated, using coleoptera, as only having reached 14-15°C (compared to nearer 18°C for southern Britain) before falling sharply at about 12,300 ^{14}C years BP to approximately 12°C and continuing at this level until the start of the Loch Lomond Stadial (Coope, 1977; Bishop & Coope, 1977). Winter temperatures for this time period have been estimated by Ballantyne & Harris (1994) as lying between 0°C and -10°C. Evidence for discontinuous permafrost remaining in some areas (Watson, 1977) supports these estimates implying winter temperatures well below zero for at least part of the stadial.

During deglaciation glacio-isostatic rebound close to the centre of isostatic recovery resulted in a relative fall of sea level. This fall has been recorded on the west coast of Scotland and on the Inner Hebrides by a complex sequence of raised shorelines formed in association with a retreating ice sheet (Dawson, 1984). One such shoreline from Islay and Jura declines in altitude away from the centre of isostatic recovery from 40m (Corpach) to 15m (western Islay) at a gradient of 0.59 m per km. Similar features have been identified from eastern Scotland (Cullingford and Smith, 1966, 1980). Only in peripheral areas where eustatic sea-level rise during deglaciation outstripped any isostatic component are the associated shorelines now submerged (e.g. Outer Hebrides, Orkney, Shetland, St. Kilda).

In addition to the erosional shoreline features associated with the Late Devensian ice sheet there are glacio-marine sediments that although undated are thought to correspond to the same time period (i.e. from prior to 16,000 ^{14}C years BP until approximately 13,000 ^{14}C years BP - Sutherland and Gordon, 1993). Onshore deposits of clays, silts and sands - termed the 'Errol beds' (Peacock, 1975) - containing arctic marine fauna may extend often well above the highest raised beaches to a marine limit as high as 40m O.D. (Peacock, 1981). Evidence supporting this assertion (Browne *et al.*, 1981) has since, however, been contested (Smith and Cullingford, 1981). The distribution of the Errol beds is chiefly on the east coast of Scotland in the Forth and Tay estuaries, however, there is some evidence to suggest their presence elsewhere including the vicinity of Stranraer, SW Scotland (Brady *et*

Offshore deposits termed the 'St. Abbs Beds' have been correlated with the Errol beds on the basis of their similar fauna and lithology (Thomson and Eden, 1977; Stoker *et al*, 1985) as have the Fladen Members of the Witch Ground Formation in the central North Sea Basin (Long *et al*, 1986).

During the early part of the Lateglacial Interstadial it was only in those areas towards the centre of isostatic uplift that sea levels above the altitude subsequently reached by the Main Postglacial Transgression (detailed below) were reached (Sutherland, 1984). Clays, silts and sands with a generally high-boreal marine fauna which are found around the coast of the Firth of Clyde, northwards along the west coast of Scotland and southwards to Girvan - termed the 'Clyde beds' - are considered to have been deposited during this time period (Peacock, 1981). Within the Clyde estuary these deposits are found to rise up to 35m O.D. although the majority of the beds reach only a few metres above O.D. (Peacock, 1981). Sea level curves produced for the head of the Firth of Clyde (see Figure 6 in Dawson, 1984) record a rapid relative sea level fall from *circa* 28m O.D. to *circa* 6m O.D. by 12,000 ^{14}C years BP after which point sea levels in this area appear to stabilise (Peacock *et al.*, 1978). Between seven and eight raised shorelines are considered to have been formed, the best defined one with a gradient of 0.33m/km, being correlated with the Main Perth Shoreline of SE Scotland (Sutherland 1981 in Sissons, 1983).

At Redkirk Point in the eastern Solway Firth the evidence that relative sea level was well below present is provided by dates from *circa* 12,300 ^{14}C years BP to *circa* 10,300 ^{14}C years BP from a freshwater peat bed at *circa* 1m O.D. (Bishop and Coope, 1977). Across Scotland in the northern North Sea Basin, evidence indicates that relative sea-levels during the same time period were between -130 and -160m (Rokoengen *et al.*, 1982 in Sutherland, 1984) implying that extensive areas of the southern and central North Sea would have been dry land.

2.2.3 The Loch Lomond (Younger Dryas) Stadial

Approximately two thousand years of milder climate was interrupted by the (re)commencement of ice accumulation in Scotland which is thought to have been the result of a southward migration of polar water (Sissons, 1979). Correlating closely with the Younger Dryas of Scandinavia, the Loch Lomond Stadial has been dated at approximately 11,000-10,000 ^{14}C years BP (Mangerud *et al.*, 1974; Gray and Lowe, 1977). More recently, however, a calibrated chronology for this stadial indicates its initiation as lying somewhere between 12,900 and 12,500 cal. yr. BP and ending between 11,600 and 11,000 cal. yr. BP (Bard and Kromer, 1996). Mapping of ice marginal features including extensive end moraine systems, ice dammed lakes and former lake shorelines as well as the distribution of hummocky moraine in Scotland has identified the location and extent of Loch Lomond glaciers (see Figure 2.3).

The most significant area of ice accumulation was the western highlands of Scotland where the resulting ice sheet is thought to have reached 400-600m in thickness. Smaller ice caps have also been identified in the SE and central Grampians (Sissons, 1983). Unfortunately the morphological evidence for ice extent is not clear everywhere (Sissons, 1979). Nevertheless, it is possible that the volume of ice in the Scottish Highlands was large enough to have had an effect on isostatic recovery resulting from Late Devensian ice sheet unloading (Lambeck, 1993a). Whether the effect would have been to slow down, halt or redepress the land affected remains unclear. To the south and west small cirque glaciers developed in Ireland, Wales, the Lake District, the Pennines and the Southern Uplands during the Loch Lomond stadial (Sissons, 1979). However, the low ice volume in each of these areas is unlikely to have had an impact on isostatic recovery (see Lambeck, 1993a).

In the western Southern Uplands - the centre of ice accumulation closest to the northern shoreline of the Solway Firth - eleven glaciers have been identified as having developed during the renewal of glacial conditions associated with the Loch Lomond Stadial (Cornish, 1981). The total area occupied by these glaciers has been calculated at 9.92 km^2 with the volume of ice estimated at 0.36 km^3. This is in comparison with the 80 km^3 estimated ice volume of the Loch Lomond glacier alone (Sissons, 1979, 1981). The impact, isostatically, of the western Southern Upland glaciers is likely to have been negligible and to have had little or no influence on the rates or patterns of glacio-isostatic recovery associated with the decay of the Late Devensian ice sheet.

Relative sea-levels during this period of ice readvance are marked around the coasts of the SW Highlands and islands by the marine erosional feature termed 'the Main Rock Platform' which at Oban has a maximum altitude of 10-11m O.D. (Gray, 1974, 1978; Dawson, 1980, 1988; Gray and Ivanovich, 1988). This feature is particularly well developed around the Firth of Lorn, the Sound of Jura and the Firth of Clyde and although initially regarded as having been produced during the Flandrian (e.g. Bailey *et al.*, 1924 in Dawson, 1984) has since been correlated with the later part of the Lateglacial Interstadial and the Loch Lomond Stadial (Sissons, 1974). Sissons (1974) further argued that the Main Rock Platform correlated with the Buried Gravel Layer - which reaches a maximum altitude of *circa* 6m O.D. - identified in E Scotland (particularly the Forth valley) and referred to both features as the Main Lateglacial

Shoreline. On the eastern side of Scotland the Main Lateglacial Shoreline can be traced as far south as Burnmouth (near Berwick) where it correlates with a submerged rock platform at -18m O.D. (Eden *et al.*, 1969 in Sissons, 1983). A similar erosional feature has also been identified in NW Scotland at the head of the Beauly Firth (Sissons, 1981). Subsequent studies (e.g. Gray, 1978; Dawson, 1980; Sutherland, 1981) have identified further remnants of this feature on the west coast of Scotland and record the shoreline passing below present sea level in NE Islay, Colonsay, W Mull, Kintyre and S Arran as a result of isostatic tilting (Dawson, 1984). The isosbases of the Main Lateglacial Shoreline indicate its probable existence below sea level in SW Scotland (see also below; Sissons, 1983).

2.3 Flandrian relative sea-level changes in Scotland

2.3.1 Introduction

The most conspicuous Flandrian shoreline in Scotland is the Main Postglacial Shoreline (MPS) which has been dated as having formed between 6,800 and 6,000 ^{14}C years BP (Firth *et al*, 1993). On the eastern and south-western coasts of Scotland this feature generally takes the form of raised estuarine mudflats - locally termed '*carse*' (Jardine, 1975). In contrast, on the western and northern coastlines of Scotland the MPS evidence is much more fragmentary and takes the form of raised gravel terraces and sand and shingle ridges (Dawson, 1982).

Differential isostatic recovery has meant that these related features occur at different altitudes. The altitudes of the shoreline fragments have, as previously mentioned, been used to develop isobase models for Scotland in an attempt to estimate isostatic uplift patterns since their formation (e.g Sissons, 1967, 1976, 1983; Firth *et al.*, 1993; Smith *et al.*, 1993, 1995). Using quadratic trend surface analysis a more recent attempt, which utilises a greater number of shoreline altitude points, suggests an elliptical pattern of uplift elongated in a NNE-SSW direction with the centre of uplift located at Rannoch Station (Figure 2.4; Smith *et al.*, 1995).

It has been suggested (Cullingford *et al.*, 1991; Smith *et al*, 1983) that the MPS may become progressively younger with increasing distance from the centre of isostatic uplift (see Figure 2.5). If true, such a diachroneity in shoreline development will have implications for the patterns of uplift in Scotland (Firth *et al.*, 1993). However, it is the paucity of data points in some areas of Scotland, particularly from the Solway Firth region, that make any conclusions from the models very tentative. Conclusive evidence that a measureable diachroneity in relative sea-level movement during the early Flandrian existed has certainly not been unequivocally demonstrated (Haggart, 1988).

An alternative quantitative model has been proposed to tackle the problems of glacial rebound and sea-level changes (Lambeck, 1993a, 1993b). In addition to raised shoreline index points (i.e. radiocarbon dated transgressive/regressive contacts of former shore features whose relation to marine levels is known and whose altitude is known) this model also considers a number of further variables including the earths' rheology and the volume and extent of the Scottish and Fennoscandian ice sheets over time (Lambeck, 1991) which allow for comparison between predicted and observed data of crustal movements and sea-level changes (*cf.* Nakada and Lambeck, 1989). The results to date, however, suggest a poor correlation between predicted and observed data (Lambeck, 1993b) indicating that such a model must be improved if it is to be ustilised to understand crustal and sea level movements in those coastal areas where observed data is limited.

2.3.2 Eastern Scotland

In the Firths of Forth and Tay stratigraphical work through the carselands has established the existence of a series of buried intercalated marine and terrestrial deposits (Sissons, 1982). Evidence of a Late-glacial low sea level is indicated by an extensive erosion surface (Buried Gravel Layer) (see above; Sissons, 1967). A change from an erosional to a depositional marine environment is marked by the occurrence of estuarine deposits overlying the Buried Gravel Layer (Sissons, 1982). According to Sissons (*op cit.*) relative marine regression during the early Flandrian resulted in the formation of three estuarine shorelines termed the High, Main and Low Buried Beaches/Shorelines in descending order of altitude. The timing of the formation of the High Buried Beach is considered to be approximately 10,100 ^{14}C years BP due to its contemporaneous relationship with features established as being of Loch Lomond Stadial age (Sissons, 1967; 1982). The Main and Low Buried Beaches have been radiocarbon dated from overlying peat as older than *circa* 9,600 and *circa* 8,700 ^{14}C years BP respectively (Sissons and Brooks, 1971; Robinson, 1993). Their existence indicates marine transgressions and regressions occurring either during the later part of the Lateglacial and/or during the early Flandrian (Sissons, 1967; 1982). The Main and Low Buried Beaches have also been identified in the Tay area and are similarly dated from overlying peat as older than 9,600 and 8,500-8,600 ^{14}C years BP (Cullingford *et al.*, 1980). In the Beauly Firth, NE Scotland, a buried estuarine surface where the regressive overlap is dated between 9,610±130 and 9,200±100 ^{14}C years BP has also been correlated with the Main Buried Beach (Haggart, 1982; 1986; 1987). Similarly at Creich in the Dornoch Firth an early Flandrian buried marine deposit of grey silty fine sand has been identified which reaches a consistent surface at -2.1m to -1.7m O.D. and is thought to have formed before 9,560±55 ^{14}C years BP (Smith *et al.*, 1992). Most of the dates obtained for the regressive overlap of the Main Buried Beach fall in the radiocarbon age plateau during the Lateglacial and early Flandrian (Becker *et al.*, 1991) and thus the similarity in the ages may be more apparent than real (Smith *et al.*, 1992).

Marine regression is considered to have ended shortly after the development of the Low Buried Beach at *circa* 8,600 ^{14}C years BP in the Forth area and more than 200 years later in the Tay region (Sissons, 1982). Relative sea level subsequently rose to deposit estuarine clays in the Firths of Forth and Tay. During this relative sea level rise, the Main Postglacial Transgression (MPT), carse clays were deposited on the peats overlying the Buried Beach sequence in all but two areas in the Forth valley where peat accumulation excluded rising sea levels (Sissons and Smith, 1965). At the culmination of this transgressive stage the Main Postglacial Shoreline (MPS) was formed and this has been dated in the Forth valley to *circa* 6,800 ^{14}C years BP from peat deposits overlying the carselands with a maximum height of 15m O.D. (Sissons, 1966; 1982). For the carselands of the Tay estuary the MPT culmination is dated between 6,679±40 and 6,100±35 ^{14}C years BP (Morrison *et al.*, 1981). A more detailed investigation at Hole of Clien on the northern side of the Tay estuary places the culmination of the MPT sometime between 6,240±80 and 6,030±80 ^{14}C years BP (Smith *et al.*, 1985).

In other areas of eastern Scotland the MPS has been identified and dated. In the Montrose basin where the carseland surface of the MPS lies at 6-7m O.D. and is considered to have formed between 7,100 and 6,700 ^{14}C years BP (Smith *et al.*, 1980). Farther north in the Ythan Valley where the carseland surface is approximately 4.5m O.D. the commencement of the MPT is dated at about 6,189±95 ^{14}C years BP having ended some time prior to 4,000±80 ^{14}C years BP (Smith *et al.*, 1983). Nearby in the Philorth Valley the MPS is at *circa* 1.5-2m O.D. with the culmination of the MPT being dated as occuring between 6,300±60 and 5,700±90 ^{14}C years BP (Smith *et al.*, 1982). Evidence from the Moray Firth, north east Scotland, suggests that the MPS reaches *circa* 9m in this area, the MPT culminating between 7,100±120 and 5,775±85 ^{14}C years BP (Haggart, 1982). In the Dornoch Firth the MPS ranges in height from 5.1 to 6.6m O.D. (Cullingford *et al.*, 1991) and has been dated as having been reached shortly after *circa* 7,000 ^{14}C years BP and well before 3,505±50 ^{14}C years BP (Smith *et al.*, 1992).

The suggestion has been made that the MPS becomes progressively younger with increasing distance from the centre of isostatic uplift (Smith *et al.*, 1983). That the MPS is measureably diachronous is also supported from age information relating to the culmination of the MPT from all but one of eight carseland sites in the Forth valley (Cullingford *et al.*, 1991). As has been stated elsewhere, the unequivocal validity of this contention has been questioned (Haggart, 1989).

Marine regression to the present level occurred after *circa* 6,800 ^{14}C years BP, but three lower shorelines occur in the MPT carse clays of the Forth valley (Smith, 1968) and four in the Tay valley (Cullingford, 1972) indicating that the fall of relative sea level was not steady. Attempts to date marine regression in the Forth valley have been of only limited success (Robinson, 1993). Farther to the north in the Philorth valley this evidence is supported by a later marine transgression dated at *circa* 4,750 ^{14}C years BP (Smith *et al.*, 1982). In the Moray Firth marine regression following the culmination of the MPT resulted in the development of five lower shorelines (Firth, 1984). Farther north at Creich (Dornoch Firth) a possible interruption in the regression to present sea level has been dated at 1,890±50 ^{14}C years BP (Smith *et al.*, 1992).

2.3.3 Northern Scotland, Orkney and Shetland

Until recently little examination of the evidence for relative sea-level change has been made along the northern coastline of Scotland, or in Orkney or the Shetland Isles. On the northern coastline of the mainland a number of raised shorelines and beaches have been recorded (Reid, 1929; Donner, 1959; King and Wheeler, 1963; Steers, 1973), however, their ages are not known. In Shetland a series of radiocarbon dates on submerged peats implies that sea-level was below *circa* -9m O.D. by *circa* 7,000 ^{14}C years BP, that it had attained -8.8m O.D. some time after *circa* 5,500 ^{14}C years BP (Hoppe, 1965) and that it had reached its present position after *circa* 4,000 ^{14}C years BP (Flinn, in Harkness and Wilson, 1979).

New data from the Wick River valley (northern Caithness) by Dawson and Smith (1997) have contributed significantly to the understanding of relative sea-level changes during the Flandrian in northern Scotland. Here the evidence from intercalated estuarine and terrestrial sedimentary sequences records a rapid rise of relative sea-level - correlated with the MPT - from as low as -3.6m O.D. to 1.5m O.D. during the early Flandrian culminating between *circa* 6,900 and *circa* 5,900 ^{14}C years BP with the formation of the MPS. Following a subsequent regression, the sediments record two further marine transgressions beginning at *circa* 4,400 and *circa* 1,200 ^{14}C years BP respectively (Dawson and Smith, 1997). This evidence shows clearly that the highest Flandrian shoreline in that area is not the MPS but a later one.

2.3.4 Western Scotland

Unlike the estuarine environments on the east coast of Scotland the sedimentary environment along much of the west coast of Scotland is not conducive to the preservation of detailed stratigraphic sequences (Sutherland, 1984). For this reason the chronology of Flandrian sea-level changes in W Scotland is less well known (Dawson, 1984).

Around the sea lochs of the Firth of Clyde the MPS, identified as sloping towards the south west at *circa* 0.062 m/km, was formed some time after *circa* 7,200 ^{14}C years BP (Sutherland, 1981). Additionally in the Loch Long - Loch Fyne area relative sea level change during the Flandrian prior to *circa* 8,000 ^{14}C years BP was dominated by regression and the commencement of the MPT is thought to have begun at least by *circa* 7,800 ^{14}C years BP (Sutherland, 1981). These dates are supported by the evidence for a marine transgression in Loch Lomond between *circa* 6,900 and 5,500 ^{14}C years BP (Dickson *et al.*, 1978). Extensive shingle ridges have been identified as being characteristic of Flandrian raised marine deposits in the Inner Hebrides (Dawson, 1982). Further to the west on Oronsay the MPT is considered to have commenced shortly after 7,420 ^{14}C years BP but had receded between *circa* 6,560 and 5,660 ^{14}C years BP (Jardine, 1978). A reinterpretation of the evidence through standardisation of the radiocarbon dates suggests the maximum of the MPT may have occurred some time after *circa* 6,900 and 7,200 ^{14}C years BP (Sutherland, 1984). The MPS in the Firth of Lorn area has been identified as sloping down from *circa* 14m O.D. in the innermost sea lochs towards the west at *circa* 0.05 m/km (Gray, 1974). An attempt to establish a more accurate relative sea-level history for the west of Scotland has been made on the Ru Peninsula (near Arisaig) using the (regionally) novel approach of isolation basin studies (Shennan *et al.*, 1993; 1994). In this way evidence from three isolation basins suggests that the culmination of the MPT occurred within the range 6.3m and 9.3m O.D. and somewhere between 6,600 and 4,000 ^{14}C years BP. This evidence is in conflict with the isobase model predictions for this area (e.g. Sissons, 1983; Firth and Haggart, 1989) which suggest a predicted height between 10m and 12m O.D. for the MPS.

Postglacial raised beach deposits are thought not to exist in the Outer Hebrides and subsequently it has been proposed that the culmination of the MPT did not exceed the height of present day sea level (Ritchie, 1966). On Benbecula a radiocarbon date of *circa* 5,700 ^{14}C years BP on peat at -0.6m O.D. (Ritchie, 1966) and one from Lewis of *circa* 8,800 ^{14}C years BP at *circa* -5m O.D. (von Weymarn, 1974) both imply transgression of the sea sometime after these dates.

Regression of the sea following the culmination of the MPT has been identified at a number of locations along the west coast of Scotland closer to the uplift centre. At the head of the Firth of Clyde in the Loch Long - Loch Fyne area five shorelines have been identified that post-date the MPS - all of which are poorly dated. However, two shorelines have been tentatively dated as having been formed at *circa* 3,800 ^{14}C years BP and shortly before 3,000 ^{14}C years BP (Sutherland, 1981). In SW Jura a staircase of thirty beach ridges exists, the uppermost of which has been correlated with the MPS (Dawson, 1982). At Gruinart, Islay, intercalating estuarine and terrestrial sediments record a falling relative sea-level in the early Flandrian before a rise, correlated with the MPT, sometime after 9,000 ^{14}C years BP (Dawson and Dawson, 1997). Estuarine sedimentation here appears to have continued until *circa* 2,000-1,500 ^{14}C years BP when relative sea-level fell to its present position. Below the MPS in eastern Mull two lower shorelines have been identified at *circa* 8m and *circa* 4m O.D. (Gray, 1974). In Argyll, evidence from Kentra Moss establishes that relative sea-level fell from 7.7m O.D. to present since *circa* 4,000 ^{14}C years BP (Shennan *et al.*, 1994), whilst further north at Glenancross the regressive contact of marine deposits is dated to 5,805±50 ^{14}C years BP at 9.03m O.D. (Innes and Shennan, 1994).

2.4 **The northern shoreline of the Solway Firth** (Figure 2.6)

2.4.1 Introduction

The raised marine deposits bordering the northern shoreline of the Solway Firth have been the focus of a number of investigations (Marshall, 1962; Jardine, 1964, 1967, 1971, 1975, 1977, 1980; Jardine and Morrison, 1976; Nichols, 1967; Bishop and Coope, 1977). The following sections attempt to synthesise the present state of knowledge on relative sea-level changes on the northern shoreline of the Solway Firth since the Late Devensian. For the location of all place names mentioned in the text refer to Figure 2.6.

2.4.2 Lateglacial sea-levels

Evidence of raised marine features at altitudes of at least 20 m O.D. in western Wigtownshire has been identified by Charlesworth (1926) and Donner (1963). Further, deposits containing an arctic fauna (Brady *et al.*, 1874), located in the Rhins of Galloway, have been suggested to be the only known examples of Errol beds on-shore in W Scotland (Peacock, 1975). The Errol beds are thought to have been laid down between the Late Devensian maximum at 18,000 ^{14}C years BP and roughly 13,500 ^{14}C years BP (Peacock, 1975). The absence of similar deposits elsewhere along the Solway Firth coastline implies that ice remained in the majority of the region and deglaciation occurred initially only in the westernmost area of Wigtownshire. This interpretation supports the contention that the marine arctic fauna of these beds indicate that deglaciation occurred prior to the oceanic polar front moving to the north of the British Isles at *circa* 13,000 ^{14}C years BP (Sutherland, 1993).

Raised marine features associated with regional deglaciation have not been identified in the eastern Solway Firth indicating that sea-level at this time was either near or below present level (Jardine, 1971) or that the area was still covered by ice. The oldest indicators of sea-level occur at Redkirk Point in the upper reaches of the estuary where peat beds spanning a time interval of 12,290±250 to 10,300±185 ^{14}C years BP indicate that mean sea-level was at least -3 to -4m below present level (Bishop and Coope, 1977). An isobase plot of the Main Lateglacial Shoreline (MLS) - considered to have been formed mainly during the Loch Lomond stadial - has indicated by extrapolation that this feature in SW Scotland is probably below (present) sea level (Sissons, 1976, 1983).

Offshore shallow (0.6m) vibrocores south-east of Wigtown Bay show evidence of salt marsh and other intertidal deposits (Pantin, 1975). These sediments which are undated and are not tied into Ordnance Datum could relate to either the Late Devensian or early Flandrian but certainly indicate relative sea-levels considerably lower than present.

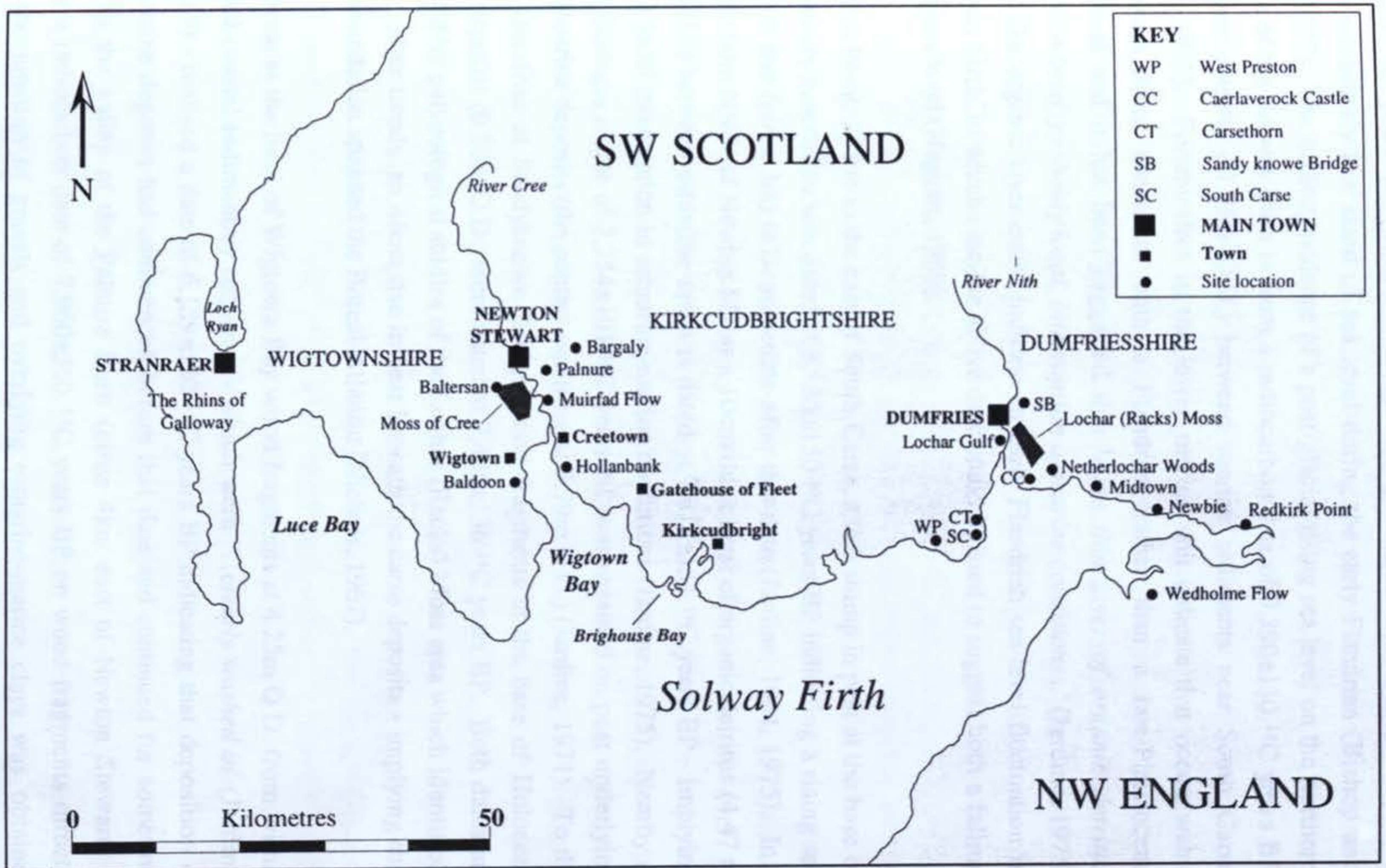


Figure 2.6 Location of sites and areas described for the Solway Firth Region

2.4.3 A chronology of Flandrian marine transgression

At Brighouse Bay an area of peat uncovered at low tide (c.0m O.D.) realised a date of 9,640±180 ^{14}C years BP which, although not associated with marine deposits, suggests a relatively low stand of sea level during the early Flandrian (Bishop and Coope, 1977). The earliest evidence of a post-glacial rising sea level on the northern shoreline of the Solway Firth is from a radiocarbon date of 9,390±130 ^{14}C years BP on organic detritus (-1.05m O.D.) between marine sediments near South Carse (Jardine, 1975). Foraminifera in the lower marine unit indicate that ocean water temperatures were consistent with a Flandrian rather than a late-Pleistocene environment and it has been suggested that '*...the thin layer of organic detritus represents a brief, probably local, interruption in marine conditions...*' (Jardine, 1975; p.178). The organic layer could indicate an early Flandrian sea-level fluctuation in the Solway Firth, in which case the above date could be used to suggest both a falling or rising sea-level (Haggart, 1989).

At Redkirk Point, 25 km to the east of South Carse, a tree stump in peat at the base of a sedimentary succession was dated at 8,135±150 ^{14}C years BP indicating a rising sea level at 10 feet (*circa* 3m) O.D. sometime after this date (Jardine, 1964, 1975). In a borehole 500m NNW of Newbie Mains a 10cm thick layer of organic detritus (4.47 to 4.57m O.D.) between estuarine sands is dated at 7,812±131 ^{14}C years BP - implying at least a local interruption in estuarine-marine conditions (Jardine, 1975). Nearby at Newbie Cottages a date of 7,254±101 ^{14}C years BP was obtained on peat underlying raised estuarine deposits (the contact occuring at 5.79m O.D.) (Jardine, 1971). To the east of Dumfries at Sandyknowe Bridge wood fragments at the base of Holocene marine deposits (0.58m O.D.) were dated at 7,426±136 ^{14}C years BP. Both dates are reinforced by palynological studies of the Lochar (Racks) Moss area which identified, amongst other trends, an *Alnus* rise in peat beneath the carse deposits - implying that marine inundation spanned the Boreal-Atlantic (Nichols, 1967).

To the west at the head of Wigtown Bay wood fragments at 4.25m O.D. from within the raised coastal sedimentary sequence - which were '*...clearly washed in*' (Jardine, 1964; p.9) - realised a date of 6,159±120 ^{14}C years BP indicating that deposition of the estuarine deposits had commenced before that date and continued for sometime after. In the valley of the Palnure Burn (*circa* 4km east of Newton Stewart) at Bargaly a radiocarbon date of 7,960±350 ^{14}C years BP on wood fragments directly below the junction of gravels and overlying estuarine-marine clays was obtained (Jardine, 1975). Using this evidence Jardine made the inference that the large area between Newton Stewart, Wigtown and Creetown was open to the marine waters of

Wigtown Bay before *circa* 7,900 ^{14}C years BP. It was only after that time (but not necessarily immediately after) that the sea began to penetrate the narrow valley now occupied by the Palnure Burn (Jardine, 1975; p182). From the above data Jardine (1975) inferred that the culmination of the MPT in SW Scotland had been achieved by approximately 7,200 ^{14}C years BP.

2.4.4 A chronology of Flandrian marine regression

Peat overlying the raised coastal deposits at Nether Locharwoods (Lochar Moss) at a height of 23 feet (9.15m) O.D. was dated at 6,645±120 ^{14}C years BP indicating that the sea-level had ceased to rise earlier in the Dumfries area than elsewhere in Northern Britain (Jardine, 1964). At Midtown, 6km east of Nether Locharwoods, a date of 6,470±280 ^{14}C years BP on peat covering brackish-water deposits provides further evidence for this assertion (Jardine, 1975). This date is also supported in broad terms from palynological analysis of peat overlying the carse deposits at Lochar Moss (Nichols, 1967). Jardine suggests for this date that conceivably the Lochar Moss area, or perhaps even a much larger part of the Solway Firth area, was cut off from the remainder of the Solway Firth basin just before *circa* 6,645 ^{14}C years BP so that thereafter peat accumulated and ultimately gave rise to Lochar Moss whilst, in areas still open to marine waters, clastic sedimentary material continued to be deposited for some time (Jardine, 1964 - p.10). Evidence of relict barrier beaches and bars across the mouth of the Lochar Gulf suggest that the isolation of this region from the rising sea could have been as a result of their development (Jardine, 1975). A date of 6,244±140 ^{14}C years BP from a peat lens overlying marine deposits at Gatehouse of Fleet would indicate a similar situation in part of the Water of Fleet estuary as noted for the Lochar Moss area (Jardine, 1971).

The carse deposits in the vicinity of Newbie Cottages (*circa* 10km east of the Lochar Gulf) are overlain by thin peat deposits and occasionally *in situ* tree stumps (Jardine, 1975). Further evidence that a marine transgression continued in this region after the exclusion of the sea in the Lochar Gulf is reinforced by dates on both the wood fragments (7.78 m O.D.) and the peat (8.18m O.D.) of 5,630±116 ^{14}C years BP and 4,290±100 ^{14}C years BP respectively; the first of which is considered to be more reliable for dating the marine regression in this area (Jardine, 1975).

At Wigtown Bay the commencement of marine regression has been established from two dates on the same sample of 6,540±120 ^{14}C years BP and 6,240±240 ^{14}C years BP on peat and wood fragments (6.38m O.D.) overlying carse deposits at Palnure (Jardine, 1975). At Baltersan, pollen analysis (Moar, 1969) across the surface peat/carse clay contact indicated that withdrawal of the sea occurred some time after 5,000 ^{14}C years BP (Jardine, 1975). Nearby at a site on the Moss of Cree a date of 4,000±100 ^{14}C years BP on twigs embedded in peat overlying the carse deposits (8.35m O.D.) broadly supports this date for marine regression in this vicinity (Jardine, 1975). On the other side of the Cree estuary at Muirfad Flow wood fragments in peat overlying carse deposits (7.92m O.D.) dated at 4,746±50 ^{14}C years BP further support a gradual withdrawal of the sea in the Wigtown Bay region (Jardine, 1975).

Jardine (1971) identified a lower shoreline surface in Wigtown Bay occurring below the surface level of the raised estuarine deposits associated with the Main Post-glacial marine transgression and is taken to indicate a temporary halt in regression. In the vicinity of Wigtown (on the western flank of the bay) this shoreline is backed by a 2-3m cliff cut into the aforementioned deposits whereas on the opposite (eastern) flank of the bay between Creetown and Kirkdale the late Flandrian coastal features are low ridges (crests at 5-6m O.D.) parallel to the present coast and consist mainly of valves of *Cardium edule* (Jardine, 1971). A radiocarbon date of 2,027±108 ^{14}C years BP was obtained on valves of *Cardium edule* from near the top of a beach ridge (5.24m O.D.) at Hollanbank (Jardine, 1971, 1975). Similarly on the western side of the bay at Baldoon a date of 2,290±95 ^{14}C years BP on valves of *Cerastoderma* sp. interstratified with fine sand (5.15m O.D.) was obtained (Jardine, 1975). Further to the east at West Preston a date on peat (5.25m O.D.) overlying (presumed) marine sands of 1,850±95 ^{14}C years BP indicates this feature to be more than confined to the Wigtown Bay area (Jardine, 1975). Associated features can be identified discontinuously along the northern shoreline of the Solway Firth such as those at Carsethorn, Caerlaverock Castle, at the mouth of Lochar Water, to the east of Midtown and less certainly farther east towards Newbie - all implying a period of relative stability during the regression of the sea to its present position (Marshall, 1962; Jardine, 1975).

2.4.5 Flandrian sea-level curves for south west Scotland

The sea-level data outlined in the preceding sections has been used to create two sea-level curves for the northern shoreline of the Solway Firth: 1) eastern Kirkcudbrightshire and Dumfriesshire (Figure 2.7A - Jardine, 1975, 1980); and 2) Wigtown Bay (Figure 2.7B - Jardine, 1975). In each case the primary points used in the construction of the curves were obtained by plotting the measured heights (metres O.D.) of relevant radiocarbon dated biogenic sediments against their age (^{14}C years BP) (Jardine, 1975). Using modern tidal data each primary point was corrected to represent a former Mean Sea Level (MSL) (Jardine, 1975).

The sea-level curve for eastern Kirkcudbright and Dumfriesshire (Jardine, 1975) indicates that relative mean sea level rose from -5.23m O.D. at 9,390±130 ^{14}C years BP to a maximum of +3.18m O.D. at 4,290±100 ^{14}C years BP after which mean relative sea level fell to +1.00m O.D. at 1,850±95 ^{14}C years BP. The curve for Wigtown Bay (Jardine, 1975) suggests a similar pattern. However, due to the allochthonous nature of the material used in the dating of the data points and the paucity of available information on present tidal levels in the bay, Jardine questions the reliability of the curve. If the curves are to be believed then they indicate that at the culmination of the MPT mean sea level was up to 1m higher in Wigtown Bay than in the Dumfries region - this is reflected in provisional isobases for the MPS in Scotland shown by Jardine (1975).

2.4.6 A critique and reinterpretation of the Solway Firth evidence

The results outlined above have undoubtedly offered an insight into the extent, chronology and direction of relative sea-level movements since the beginning of the Flandrian for the northern shoreline of the Solway Firth. A number of criticisms have, however, been leveled at certain aspects of this work (Haggart, 1982; 1988; 1989). Haggart (1982) noted a distinct dissimilarity in the shape of the Solway Firth relative sea-level curves and those produced for other areas of Scotland. He attempted to establish whether the differences in the curves are due to regional isostatic and/or eustatic variations or whether they result from inadequacies in data collection and interpretation (Haggart, 1982). The eastern Solway Firth sea-level curve was considered in most detail due to the reliability of the data points used in its construction (see above).

The following is a summary of alternative interpretations suggested by Haggart (1989) for the eastern Solway Firth data. Haggart maintains that the evidence from the South Carse borehole could be interpreted equally to represent either a fall or a rise in relative sea level. The data point from the tree trunk at Redkirk Point could indicate too old an age for any inferred rise in relative sea level. The data point from Newbie Mains is derived from a sample incorporating material from a regressive and transgressive contact and therefore does not represent a single reference water level. Three further data points from Newbie Mains are relevant as indicators of sea-level change but two were left out because they did not '*lie on the general line of*...[the sea-level]...*curve*' (Jardine, 1975). The data point from Sandyknowe is based on a sample of wood fragments from the lower levels of a Holocene marine silty fine sand which overlies fluvioglacial sands and gravels. The fragments are probably allochthonous and there is neither indication of a relation to a tidal level nor independent evidence for direction of sea-level movement. The two data points from Nether Locharwoods and Midtown can be interpreted as reflecting a regional fall in relative sea level. The two data points used to delimit the maximum level on the original curve are from allochthonous wood fragments and a 7cm slice of peat from the basal contact of a peat at Newbie Cottages. Although it is not known if there was a delay in the initiation of peat growth following the removal of marine conditions, the two dates may simply relate to a later stage in the general fall in relative sea level after *circa* 6,600 ^{14}C years BP.

The above reinterpretations of the evidence have been used to construct a new sea-level curve for the eastern Solway Firth (see Figure 2.8 after Haggart, 1989). In an attempt to account for inadequacies in dating techniques and the problems of sediment compaction each index point in this curve (as with those redrawn from other regions of Scotland) has had error values added to both age and altitude axis: the effect of this is to create a sea-level band rather than a single-line curve (Haggart, 1989). The differences between the eastern Solway Firth curve and those from other areas of Scotland are greatly reduced leading Haggart to the conclusion that...

> '..*many of the differences between the sea-level curves...can be explained through differences in the use and application of the ^{14}C dated material to sea-level studies and the interpretations inherent in the different approaches used. It is proposed that the Solway Firth areas can be looked upon as similar in isostatic and eustatic response to other areas of Scotland and differences are more apparent than real.*' (Haggart, 1982: p73)

Curiously, neither Jardine nor Haggart identified that the radiocarbon dates on the regressive contacts from both the Cree Estuary and the Lochar Gulf regions indicate distinct clustering around two time periods: *circa* 6,000 ^{14}C years BP and *circa* 4,200 ^{14}C years BP. The small number of dates make this suggestion only cogitative however and the data may well reflect a more complex sea-level picture than just a slow regression during the mid-Flandrian.

2.4.7 Rationale behind the current research

The above account and critique of the current knowledge of relative sea-level studies for the northern shoreline of the Solway Firth indicate clearly the need for further research in this region. The undertaking of more detailed litho- and bio-stratigraphical investigations is of primary importance to the understanding of relative sea-level changes in this area. More recent studies have indicated the absolute necessity of determining the index points used for the construction of relative sea-level curves with greater accuracy (e.g. Shennan, 1986a; 1986b). It is in these areas that the present research will develop the understanding of Flandrian relative sea-level movements in the Solway Firth.

Chapter 3 Methodology and Techniques

3.1 Introduction

Tooley (1978) outlines the problems of ambiguity associated with morphological, stratigraphical and radiometric dating methods in sea-level studies. He maintains that without consideration of microfossil evidence such work is vulnerable to inaccurate interpretation. In the present study both foraminifera and ostracod analyses have been undertaken in an attempt to determine and highlight their potential application to studies of relative sea level change. In accord with similar research elsewhere (e.g. Haggart, 1982; Smith *et al.*, 1992) pollen and diatom analyses have also been employed in this study of sea level change in the Solway Firth. Where appropriate mollusc analysis has been undertaken. This section reviews the field and laboratory techniques used in this research and is accompanied by an overview of the application of each palaeobotanical analytical technique to sea level change research.

3.2 Field techniques

3.2.1 Morphological mapping

All features below approximately 20m O.D. within the confines of the sites studied were mapped at a scale of 1:10,000 using the symbols adopted by Sissons *et al.* (1966).

3.2.2 Lithostratigraphical survey

The objective of the lithostratigraphical survey at each site was to establish the nature and extent of the sub-surface Flandrian sedimentary units. The stratigraphical survey of each site was undertaken using an Eijkelkamp gouge sampler (1m chamber), a Hiller peat sampler (0.33m chamber) (see Fries & Hafsten, 1965) and also a powered Stitz percussion borer where necessary (1m chamber). The strategy employed for each site varied according to its extent and the depth of the stratigraphy to be examined. For example, boreholes were put down on a grid system of *circa* 20m at the small inlet site of Brighouse Bay whereas for the much more extensive raised estuarine deposits that flank the Cree estuary a series of transects was undertaken with boreholes spaced 200 metres apart at the centre of the valley and 5 to 10m apart at the valley margins.

Lithostratigraphical investigations in the valley of the Cree estuary recorded a soft rock sedimentary sequence in excess of *circa* 20m. In a previous study the depth of fossil estuarine muds in this area were known to be at least *circa* 25m in thickness (Jardine, 1975). The practicability of undertaking a systematic coring programme to these depths across this region would have been very difficult with the available equipment. The extendible Eijgelkamp gouge can theoretically be used to considerable depths in soft sediments but the pressures imparted in pushing through the silts and clays meant that it was not sensible to continue past about 13m. Where highly compacted buried peat was present within the silts and clays it was commonly impossible to penetrate using the gouge. The Hiller peat sampler was more effective at penetrating to depths greater than 13m and could be utilised to screw through compacted peats and thin gravel layers. This system was, however, very time consuming and often unreliable. The difficulties of undertaking a lithostratigraphical survey in the valley of the Cree estuary can only be practically overcome by using a rig supported, mechanised, coring system which cases the hole during penetration. The time and resources to provide such equipment at the detailed scale required was not available in the present investigation, although a fortuitous opportunity late in the programme of fieldwork to obtain cores during a demonstration programme given by the Dutch Geological Survey coring team was taken advantage of.

At all sites the lithostratigraphical descriptions of each sediment unit were undertaken in the field and, where drawn in this thesis, the symbols used are based freely on the modified Troels-Smith (1955) scheme as proposed by Tooley (1978). On completion and analysis of the lithostratigraphical data sampling sites were chosen for microfossil, macrofossil and radiometric analyses.

3.2.3 Levelling

A Nikon AE Auto-level and a Geodimeter 422LR were used to determine the altitudes of landforms and deposits at each site investigated. All altitudes are based upon Ordnance Datum (Newlyn). The closing error of each traverse was never more than ±0.05m.

3.2.4 Sediment sampling for laboratory analysis

Field sampling to recover sediment for laboratory analysis and future radiometric dating was undertaken using a Stitz percussion borer. Three boreholes (CWF/A, BB/D/B2 and BB/D/B3) were undertaken by the Dutch Geological Survey coring unit using a semi-automated drilling rig. Where samples were solely required from marine/terrestrial sedimentary boundaries a large bore (8cm diameter) Russian corer (0.3m length) was used (as detailed by Jowsey, 1966). At a limited number of locations it was possible to clean an open face of sediment from which a monolith sample was taken. This had the added advantage of avoiding compaction during sediment recovery. All cores and monoliths were marked, wrapped and sealed on site and then returned to the laboratory where they were stored in either a deep freeze or a cold store unit at 1°C until required for sub-sampling and analysis.

3.3 Laboratory techniques and their applications to sea-level research

3.3.1 Foraminifera analysis and sea-level studies

Foraminifera are protozoans that produce four basic shell types - calcareous, agglutinated, porcelaneous and organic walled - of which all but the last fossilize readily making them suitable for palaeoenvironmental analysis (Scott & Medioli, 1986). Whereas diatoms, molluscs and ostracods have evolved to inhabit nearly all aqueous environments, foraminifera are almost exclusively restricted to marine habitats. Nonetheless, foraminifera have become invaluable tools in palaeoenvironmental analysis, in palaeoclimatic reconstruction and in Quaternary stratigraphy (Lowe & Walker, 1996). In the marginal marine environment (i.e. marsh; estuarine; lagoonal) the abiotic factors such as salinity, water temperature and water depth (foraminifera are in the main benthonic) are considered to be the primary control of foraminifera distribution (Scott & Medioli, 1986).

Literature concerning the modern distribution and ecological preferences of the foraminifera species that live in British coastal waters is growing (e.g. Adams and Haynes, 1965; Coles, 1977; Coles and Funnell, 1981; Culver and Banner, 1978; Haynes, 1973; Haynes and Dobson, 1969; Murray, 1971, 1979, 1991; Murray and Hawkins, 1976). One of the most comprehensive studies of living foraminifera was undertaken around Cardigan Bay (Haynes, 1973). Murray (1971) at a similar time published his *'An Atlas of British Recent Foraminiferids'* that dealt with the British Isles as a whole rather than a single regional study - subsequently a more user-friendly manual entitled *'British Nearshore Foraminiferids'* was produced (Murray, 1979). The aim of the latter publication was to provide only an introduction to foraminifera analysis with a summary of the ecology and form of the main foraminifera common to the British Isles. Consequently the coverage of the complete British foraminifera fauna was not comprehensive nor were the ecology and distribution of each species given in any great detail.

More recently Murray has attempted to summarise a number of recent investigations of modern foraminifera distributions into one volume (Murray, 1991). In this he draws on the evidence from the estuaries of the North Atlantic seaboard of Europe and Africa and has identified a number of distinctive foraminifera assemblage '*associations*'. This method identifies a link between specific estuarine and marine environments (including water depth, substrate, salinity and temperature) with a dominant foraminifera species and a list of possible subsidiary species that may also be present. Murray's study (1991) provides an unrivaled and excellent framework from which interpretations of palaeoenvironmental foraminifera assemblages can be related to a modern environment of deposition.

Investigations of recent foraminiferal assemblages and their ecological requirements have established effectively a relationship between associations of particular species, estuarine depositional environments and tidal levels (e.g. Brady and Robertson, 1870; Haynes & Dobson, 1969; Murray, 1973; Coles, 1977; Scott & Medioli, 1978, 1986; Coles and Funnell, 1981; Jennings & Nelson, 1992). As a consequence this ability to distinguish specific estuarine environments from fossil sedimentary sequences has allowed foraminifera analysis to be utilised in studies of relative sea-level change and coastal evolution (Haynes & Dobson, 1969; Murray & Hawkins, 1976; Haynes *et al.*, 1977; Culver & Banner, 1978; Kidson *et al.*, 1978; Brew *et al.*, 1992; Huddart, 1992; Boomer & Godwin, 1993; Haslett, 1997). The effectiveness of this application of foraminifera is, however, restricted by the accuracy with which a modern species association relates to a tidal level. One of the most recent schemes of foraminiferal biozones for British waters is outlined below (adapted by Boomer & Godwin, 1993):

Zonation Index Species: Foraminifera

[based on Coles (1977) and Coles & Funnell (1981)]

Upper saltmarsh

Zone Ia *Trochammina inflata*

Zone Ib *T. inflata, Jadammina macrescens*

Lower saltmarsh

Zone IIa *T. inflata, J. macrescens, Ammonia beccarii* vars *limnetes/tepida, Haynesina germanica, Elphidium williamsoni.*

Zone IIb *A. beccarii* vars *limnetes/tepida, H. germanica, E. williamsoni, Elphidium excavatum* forma *lidoensis*

Zone IIc Large *A. beccarii* together with some (Marsh Creeks) Miliolids and a mixture of mainly saltmarsh and some sub-tidal morphospecies

High Intertidal Flat

Zone IIIa *A. beccarii, H. germanica, E. excavatum* formas *excavata/selseyensis* plus a small percent of small, size sorted *Elphidium earlandi, Elphidium gerthi, Elphidium magellanicum* and other shelf species.

Transition zone

Zone IIIb A mixture of IIIa and IVa assemblages sub-tidal species becoming more important.

Tidal Flat Channel

Zone IIIc As for IIc but saltmarsh species are rarer, and small, size-sorted, transported shelf material more common.

Low Intertidal Flat

Zone IVa *A. beccarii, H. germanica,* 4-10% *Elphidium oceanensis* and/or *E. excavatum* forma *clavata.*

Sub-tidal Flats (b) & Channels (c)

Zone IVb/c *A. beccarii, H.germanica,* 11-50% *E. oceanensis* and/or *E. excavatum* forma *clavata.* Milliolids, *Haynesina depressula* & *E. incertum* more common here than elsewhere.

In this and similar investigations of modern foraminifera distributions in British near-shore environments the actual relationship between a species association, a sedimentary facies and a specific tidal level and/or range is rarely specified. In one rare example an investgation of the Dovey estuary recorded a major drop in foraminifera abundance at the low marsh/high marsh interface (which approximates to Mean High Water of Spring Tides [MHWST]) and that foraminifera species such as the agglutinating *Trochammina inflata* flourish in the uppermost of the intertidal zones (Haynes and Dobson, 1969). Here a low marsh assemblage comprised of estuarine calcitic species and dead allochthonous marine species was considered to lie between 2.36 and 1.36m O.D..

Detailed investigations of foraminifera from the saltmarshes of California and Nova Scotia have shown that distinct faunal groupings that inhabit the vegetated marshes that exist in distinct biozones between higher high water (HHW) and mean sea level (MSL) can be related accurately (±10cm) to a former sea-level (Scott & Medioli, 1978, 1986). Support for this work has since been provided by a similar study in Oregon tidal marshes (Jennings and Nelson, 1992).

The difference in the accuracy of the foraminifera zones between the similar studies from North America and the British Isles is marked. Prince (1988) suggests that these differences are undoubtedly related to the dissimilar tidal regimes of the two regions - being meso-tidal and macro-tidal respectively. Of course, a more appropriate comparison of the studies may require that the high marsh, as opposed to the low marsh, biozone of the Dovey estuary is related to a tidal level. Scott and Medioli (1980) have certainly noted that the foraminifera zonal ranges do not appear to increase proportionally with increasing tidal range.

More recently, however, a study of the marsh foraminifera from the Great Marshes of Massachusetts has shown that the vertical zonation of foraminifera as proposed by Scott and Medioli cannot be applied to this region (de Rijk, 1995). In this study de Rijk observes that the vertical zonation concept of organisms is based on the principle that the ecological parameters have a linear relationship with elevation - this principle can not be applied to the Great Marshes where salinity and flooding regime vary independently of the surface elevation. Therefore with each salt marsh having its own foraminiferal 'fingerprint' the suggestion that a surface study is an essential first stage in assessing the value of foraminifera as a palaeo-ecological indicator was concluded (de Rijk, 1995).

Consequently an investigation of the modern distribution of foraminifera has been undertaken in the Cree estuary region (taken to include Brighouse Bay) as part of the present research (Chapter 4). In this way it is possible that an association of foraminifera species from the fossil sediments of the Cree estuary can be related to a former intertidal environment of deposition and a former tide level.

In addition to these applications to relative sea-level studies foraminifera analysis can also be used to a certain extent as a biostratigraphical marker. The tolerance of particular species to relatively colder waters has meant that species such as *Elphidium excavatum* forma *clavata* (see Miller *et al.*, 1982) can be used to indicate those sediments deposited during glacial conditions (e.g. Peacock *et al.*, 1977, 1978, 1992; Lord, 1980; Austin & Kroon, 1996).

As with the other microfossils the problems of *post mortem* transport make interpretation of a fossil assemblage more difficult. Transport mechanisms of foraminifera can include bed load and suspended load, floating plants, ice, turbidity currents and mass flow in aqueous environments and by wind on land - of which the first two factors are considered the most important processes (Murray, 1991). In the dynamic environment of the estuary these problems are enhanced. In one study (Wang & Murray, 1983) a clear correlation between tidal range and the proportion of exotic tests (i.e. allochthonous) introduced as sediment load was established. The results showed that microtidal estuaries have only a small component of transported tests, mesotidal examples have a moderate proportion and macrotidal estuaries commonly have >50% exotic tests in the muddy intertidal sediments. The exotic component was easily identified due to small test sizes and the paucity of living specimens. Additional factors that may affect assemblage composition are sediment mixing, test destruction and dissolution of tests (Murray, 1991).

In the fossil record identifying the allochthonous component from the autochthonous is essential for accurate assemblage interpretation. In modern samples Murray (1982) compared "live", "dead" and "total" foraminifera assemblages and showed that there was a good relationship between all three. This augers well for studies of the fossil record where only the "total" population is preserved. In this study a qualitative evaluation of assemblage composition was undertaken, looking at test preservation and the existence of all growth stages from juvenile to "adult", in accordance with similar studies (e.g. Culver & Banner, 1978). Also the likelihood of species co-existence was evaluated using knowledge of species' modern ecology.

Foraminifera analysis in this study has, therefore, been employed as a multi-purpose palaeoecological tool. Primarily it has been used to determine broad changes in the environment of deposition of fossil estuarine and marine sediments. By using the known ecological requirements of both individual species and associations of species the identification of changes in water depth (including a lowering in the intertidal zone) over time is possible and changing relative sea levels can be determined. Secondly, through detailed sequential sampling and analysis of the foraminifera throughout fossil sedimentary sequences it is possible to determine the presence or absence of depositional lacunae; these results can also be utilised to evaluate whether a change from marine/estuarine sedimentation to terrestrial conditions was uninterrupted. Finally the temperature requirements of certain species can be used to indicate changing water temperature. In sedimentary sequences that may extend back into the Devensian glacial stage this application is of vital importance.

3.3.2 Ostracod analysis and sea-level studies

Ostracods are small, bivalved, crustaceans with calcareous shells that grow by ecdysis (moulting) shedding their old shell and secreting a new one approximately twice the size (Van Harten, 1986). A group that has existed since at least the Cambrian, ostracods now inhabit nearly all types of natural aquatic environment from freshwater to marine (Van Harten, 1986) making them suitable for many forms of palaeoenvironmental analysis (Whatley, 1983). Literature on studies of sea-level changes using ostracods is growing (e.g. Haynes *et al.*, 1977; Kidson *et al.*, 1978; Robinson, 1980; Penney, 1985; Prince, 1988; Boomer and Godwin, 1993) and is testament to their potential and applicability in this research area (see Penney, 1987).

The influence of environmental salinity, water temperature and water depth on ostracod distribution are of greatest relevance to the reconstruction of former sea levels. In nearshore/estuarine environments salinity is one of the main ecological factors influencing the distribution of individual ostracod taxa making it possible to divide the family into freshwater, brackish and marine groupings (Van Harten, 1986). Athersuch *et al.* (1989) use a classification system employing 'non-marine' as a term to define all terrestrial based water bodies. In addition brackish waters are divided into two: 1) marine species that can tolerate reduced salinities and 2) brackish-water ostracods which are only found in waters of less than normal marine salinity (<35‰).

The geographical distribution of ostracods is controlled to a greater extent by water temperature and in the British Isles today there are those species which are eurythermal (Athersuch *et al.*, 1989; Wood and Whatley, 1994). When analysing fossil sequences that span inter-glacial/glacial time periods the thermal tolerance of particular species can be used in the development of effective ecostratigraphies. The majority of ostracods are benthonic and exist within rather well-defined depth limits (Van Harten, 1986). Identification of such characteristic species within the fossil record can aid in the reconstruction of former sea-levels although, due to the complexities of post-mortem transport (taphonomy), the accuracy of water depth estimates is limited (Van Harten, *op cit.*).

Identifying tidal level markers in the fossil record is paramount when reconstructing former relative sea-levels. Therefore, by analogy and assuming taxonomic uniformitarianism, an understanding of present day ostracod faunal associations and their relationship to a tide level or near-shore environment is essential. Investigations into living ostracods from around the coastline of Britain (e.g. Brady, 1866; Brady and Robertson, 1870; Wall, 1969; Whatley & Wall, 1969; Whittaker, 1972; Horne, 1980) has meant that current knowledge of recent brackish/marine water ostracods and their ecological tolerances is well established (Athersuch *et al.*, 1989). Problems associated mainly with *post mortem* transport, however, in the deep water environments mean a low resolution of accuracy in relating ostracod assemblages with a tidal level (Van Harten, 1986). In marginal marine and brackish water habitats this resolution is enhanced (Van Harten, *op cit.*).

The stresses caused by semidiurnal changes in water depth, salinity and temperature within these nearshore estuarine environments have led to the establishment of characteristic, low diversity, high productivity ostracod faunas which can be recognised within the fossil record making more accurate tidal level associations possible (see Peypouquet, 1979-1980). A comparison of recent ostracod assemblages along the south coast of England from three different marine environments [i.e. normal marine conditions (Weymouth Bay), a tidal lagoon (The Fleet) and a small estuary (Christchurch Harbour)] outlines clearly the role that salinity plays in influencing the distribution of British coastal ostracods (Whittaker, 1972; Athersuch *et al.*, 1989). Penney (1987) focuses particularly on the importance of the estuarine environment for identification of tidal markers in the ostracod fauna and provides an ecozonation system - summarised below and used in the present study for assemblage zonation - that distinguishes four main facies using life assemblages from estuaries around NW Europe:

Ostracod life assemblage zonation (NW European estuaries)

[after Penney (1987)]

Environment	Ostracod characteristics and common species
Salt marsh	Normally devoid of living ostracods.
	Temporary residence of freshwater/euryhaline species possible.
	Rich ostracod faunas often occur in marsh creeks although assemblage can be similar to mesohaline lagoon associations (e.g Christchurch Harbour, England - Whittaker, 1981).
	Species present: *Cyprideis torosa* (Jones); *Leptocythere porcellanea* (Brady); *Loxoconcha elliptica* (Brady); *Cytherois stephanidesi* (Klie); *Callistocythere murrayi* (Whittaker); *Leptocythere lacertosa* (Hirschmann); *Leptocythere castanea* (Sars); *Cytherois fischeri* (Sars).
Mud flat	Can be either vegetated (Lower Marsh) or bare mud.
	Sparse populations of freshwater ostracods in upper reaches of estuaries.
	As salinity increases down-estuary euryhaline species appear, often in very large numbers and can get dominance by one species (monospecifism).

Species present: *Cyprideis torosa* (Jones); *Leptocythere castanea* (Sars); *Leptocythere lacertosa* (Hirschmann); *Cytherura gibba* (O.F.Müller); *Loxoconcha elliptica* (Brady); *Cytherois fischeri* and *Xestoleberis nitida* (Liljeborg)

Sand flats Sometimes hard to differentiate from mud flat facies using ostracods. Intertidal sand flats are extremely unproductive/sparser than on mud flats. Species diversity increases as normally situated in the lower, more exposed part of the estuary where marine species can colonize (normally) temporarily. Replacement of euryhaline mud flat species by intertidal rock pool and shallow eulittoral zone species.

Species present: *Aurila convexa* (Baird); *Cythere lutea* (O.F.Müller); *Hemicythere villosa* (Sars); *Paradoxostoma* spp.; *Semicytherura* spp.; *Elofsonia pusilla* (Brady & Robertson). Muddy sand flat *Leptocythere lacertosa* dominates but is replaced by *L. psammophila* (Guillaume) in sandy estuaries. Occasionally get *Leptocythere pellucida* (Baird); *Pontocythere elongata* (Brady); *Urocythereis britannica* (Athersuch).

Channel Lack of ostracods in this zone due to oxygen deficiency, erosive tidal currents and lack of subaerial exposure.

Distinguishing fossil life assemblages (biocoenoses) from the derived fossil death assemblages (thanatacoenoses) due to post-mortem transport both laterally and vertically can be used to reduce errors in palaeoenvironmental reconstruction (Whatley, 1983). Selective *post mortem* transport appears to be related to the variety of hydrodynamic properties of the ostracod carapace (i.e. size, shape, whole shell or loose valve). An increased understanding of these processes makes it possible to separate biocoenosis from the thanatocoenosis (Whatley, 1983).

Recent ostracods generally have eight successive larval stages before reaching adulthood and sexual maturity (Athersuch *et al.*, 1989). Once shed the juvenile ostracod valves (instars) are often incorporated into bottom sediments and fossilised. This process allowed Whatley (1983) to identify three basic types of fossil assemblage by studying population age structure of individual species. With the complexities of estuarine hydro-dynamics this scheme can aid the identification of autochthonous species from the allochthonous component such as freshwater or deep marine species (Penney, 1987; see also Figure 2 in Whatley, 1983). Only by reducing/eliminating these errors from the fossil ostracod record can the prediction of former sea-level positions be made with accuracy.

In this study ostracod analysis is utilised in much the same way as the foraminifera analysis. However, because these animals are known to not inhabit the vegetated salt marshes, where agglutinating foraminifera can flourish, the resolution of this technique in determining a former tidal level is poor. Therefore ostracod analysis is used here primarily to reconfirm and supplement the results provided by the foraminifera analysis.

3.3.3 Mollusc analysis and sea-level studies

Molluscs, invertebrates in which the soft parts of the body are generally enclosed within the calcareous shells, can be divided into two principal groups: Gastropoda (single shell) and Bivalvia (two valves) (Lowe & Walker, 1996). In common with ostracods they have evolved to inhabit nearly all forms of natural aquatic and terrestrial environments and are generally well preserved in fossil sedimentary sequences. As with diatoms, foraminifera and ostracods, the influence of environmental salinity, water depth and water temperature on mollusc distribution makes this technique a valuable data source for the reconstruction of former sea-level studies. The role of marine molluscs as indicators of former sea-level stands and the potential to differentiate between littoral, shallow- and deep-water environments from specific species and faunal groups has been adequately reviewed (Petersen, 1986). As with the other microfossils the importance of determining the degree of *post mortem* transport in fossil sequences is essential in establishing the palaeoenvironment. Interestingly, the literature on the application of mollusc analysis in the fossil record generally separates the usage of fresh and land species from the marine. In doing so the potential of this technique in identifying changes from fresh to saline water through fossil sedimentary sequences has been neglected.

3.3.4 Foraminifera, Ostracod and Mollusc analysis: Laboratory procedure and identification

Analysis of the foraminifera, ostracods and molluscs at each site was undertaken using the same sediment sample for each faunal group. At Brighouse Bay, through the shelly marl and gyttja sediments, contiguous samples of 2-3cm core depth were taken (approximately 40 or 60cm³ respectively). Through the deep sequences of fossil estuarine deposits that flank the Cree Estuary contiguous sampling would not have been practicable and therefore smaller 1cm wide sub-samples of 10g were taken - initially at 50cm intervals for preliminary investigation after which closer samples were taken where distinct faunal changes were taking place. At Brighouse Bay the sediments were wet sieved (aperture = 63μm) to remove the finer particulate matter and dried in an oven at 40°C. For the silty clay estuarine deposits each sample was boiled (*circa* 30 minutes) to break down the sediment before being wet sieved and oven dried. Once dried each sample was then sieved through a 112μm aperture mesh and only the larger portion analysed quantitatively for each of the faunal groups. The smaller portion was scanned and any additional information associated with juvenile populations was recorded.

Although Pielou (1979) disputes that a count of 300 individuals (foraminifera) is adequate Murray (1991) observes that when 250 or more individuals are counted, the relative proportions of the component species are relatively constant. Culver & Banner (1978) have clarified that counting more than 400 specimens would have entailed a disproportionate amount of time to attain a small increase in the accuracy of results. Thus, at each level a minimum of 300 foraminifera tests were identified using a stereoscopic binocular microscope. For consistency ostracod valves (carapaced forms equal two valves) were also counted to at least 300 for statistical reliability. In those samples with less than 300 individuals all foraminifera and ostracods were identified. Due to the variability of the number of individuals counted per level (0 to >300) the conversion of the raw data to percentages was not considered appropriate.

Quantitative analysis of molluscs from fossil sediments generally requires a large amount of sediment (1 to 2 kg) to achieve a statistically viable assemblage. Recovering such an amount of sediment from the deep estuarine sediments that flank the Cree Estuary was impractical due to limitations of the coring technique. Therefore in this study mollusca analysis was only undertaken systematically on the marls at Brighouse Bay (see Chapter 5) where there was an abundance of individuals in a relatively small sediment sample. For each level prepared for analysis at this site all mollusca were identified. The molluscs from Brighouse Bay were identified by Mr C. Gleed-Owen (Centre for Quaternary Science, Coventry University) although the author takes full responsibility for method of presentation, description and interpretation of this data.

As a basis for palaeoecological reconstruction it is important, when presenting the information diagrammatically, to concentrate upon particular environmental characteristics related to the aims of the research. In this way any patterns or trends in the assemblage can be augmented. In the present study, with the focus on changing sea levels, the importance of salinity and/or the relationship to a marine environment on the distribution of each microfossil has been emphasised. No standard systems have been developed for grouping either foraminifera or ostracods. Thus the foraminifera are separated into five categories (after Murray, 1979): 1) Marsh, 2) Brackish, 3) Brackish/Marine, 4) Marine (inner shelf) and 5) Marine (planktonic). The ostracods have been grouped informally into one of the following five categories: 1) Freshwater, 2) Freshwater (low salinity), 3) Brackish, 4) Marine/Brackish and 5) Marine. Although well established grouping systems are known for both and freshwater mollusca (see Lowe & Walker, 1996) for the purposes of the present study all freshwater species have been grouped together. The marine molluscs have been separated into the brackish and the fully marine species. For complete species lists and ecological information of the main foraminifera, ostracoda and mollusca see Appendix B.

It is acknowledged by the author that each of the informal grouping systems for the foraminifera, ostracoda and mollusca assemblages outlined above can not be rigidly enforced. Species cross-over between groups is possible and it is ultimately the association of species that provides the environmental detail. Nonetheless, these groupings are considered useful for understanding the broad environmental changes, particularly for the non-specialist.

The references used for foraminifera identification were Haynes (1973), Murray (1979) and Haynes, (1981). The identification of the ecomorphotypes of *Elphidium excavatum* and *Ammonia beccarii* were undertaken using the definitions of Miller *et al.* (1982) and Murray (1979) respectively. The references used for ostracod identification were Athersuch *et al.* (1989), Mizen (1986), Henderson (1990), Griffiths (1995) and the unpublished records of Dr. A.Wood (Department of Geography, Coventry University). Examples of the main foraminifera and ostracod species present were photographed using a Scanning Electron Microscope (SEM) (see Appendix C).

3.3.5 Diatom analysis and sea-level changes

Diatoms are microscopic single celled algae that secrete siliceous shells and are known to exist in a wide range of ecological niches ranging from freshwater environments to deep oceans (Lowe and Walker, 1996). The method, application and potential of diatom analysis as a palaeoecological indicator has been reviewed (Battarbee, 1986). Palmer and Abbott (1986, p.459) have outlined the use of diatoms in sea-level studies offering the following fourfold summary of their advantages over other techniques:

1) diatoms are widespread in natural aquatic environments;

2) many species prefer specific salinity conditions;

3) the silica constituting the valves is relatively resistant to chemical alteration after burial;

4) diatoms are often preserved in association with radiometrically dateable carbonaceous material.

The dominance of salinity in controlling the distribution of diatoms (Battarbee, 1986), however, is now questioned and the combination of life form, substrate preference and salinity tolerance must all be considered in diatom assemblage interpretation (Nelson and Kashima, 1993). Many of the factors that affect the distribution of diatom species in the intertidal zone are directly related to elevation, but because diatom assemblages result from complex ecological interactions the role of any single factor in controlling the composition of an assemblage is difficult to establish (McIntire & Moore, 1977). Undoubtedly an understanding of the ecology (e.g. Admiraal, 1984) and vertical zonation of recent benthic diatom assemblages within the intertidal zone is a prerequisite for using fossil diatom assemblages to estimate past sea-level changes (Simonsen, 1967; Nelson & Kashima, 1993). Such a zonation system for north west Europe is being developed (Vos & de Wolf, 1993a).

Diatoms are light and easily transported and, as with other microfossils, accounting for *post mortem* transport remains problematic. In the estuarine environment this problem is enhanced where a complex admixture of marine, brackish and freshwater forms are often encountered (Brockmann, 1940; Lowe & Walker, 1984; Vos & de Wolf, 1993a). Accounting for the allochthonous element in an assemblage as a result of translocation by water (rivers, overland run-off and tides) and wind transportation (e.g. sea spray) is crucial to environmental interpretation (Du Saar, 1967). In some cases, the allochthonous diatom population can exceed the autochthonous (Simonsen, 1969). Dissolution of the siliceous diatom frustule post deposition is also possible particularly in brackish and freshwater environments where conditions are highly alkaline or very acid (Round, 1964). Techniques designed to overcome these problems have been developed. Simonsen (1967) for instance suggests that only the benthic diatom species should be counted to achieve the autochthonous component of the diatom assemblage. An alternative and more precise method for distinguishing the allochthonous from the autochthonous element of palaeoecological diatom studies based on a number of diatom- and non-diatom-related criteria (Vos & de Wolf, 1988) has since been developed .

Nevertheless the usage of diatom analysis in sea-level change research, and particularly in fossil estuarine sedimentary sequences, is well developed (e.g. Tooley, 1978; Haggart, 1982; Smith *et al.*, 1992; Vos & de Wolf, 1993b; Healy, 1995). Specific applications of diatom analysis such as the reconstruction of sedimentary facies and palaeo-tide levels, sea-level change and related trans- and regressive coastal developments and palaeo-salinity gradients have subsequently been clarified (Vos and de Wolf, 1994). The objective of diatom analysis in this study, where applied, was to identify as accurately as possible the points of marine transgression and regression through the identification of changing frequencies in the abundance of marine, brackish and freshwater species. In addition the characterization of sedimentary environments was undertaken where possible.

In order to achieve these objectives an appropriate classification system was required to aid interpretation. Numerous diatom classification systems according to salinity have been developed (Kolbe, 1927; Hustedt, 1953, 1957; Simonsen, 1962; de Wolf, 1982; Vos & de Wolf, 1993a). In this study the classification system suggested by Vos and de Wolf (1993a) based on the factors of life form and salinity has been adopted. This system was developed specifically for use in the clastic deposits of coastal wetlands and was therefore considered ideal for reconstructing palaeosalinity gradients, palaeotide levels and identifying trans- and regressive coastal developments in the present study area.

3.3.6 Diatom analysis: Laboratory Procedure

Sampling for diatoms was only undertaken across sedimentary boundaries. A small (*circa* 0.5g) amount of sediment was treated with 30% hydrogen peroxide and boiled on a hot plate to remove all organic and shell materials. To remove as much of the clay fraction as possible each sample was centrifuged at least 8 times in distilled water. A small amount of the remaining sediment suspension was then dried on a cover slip and mounted in Naphrax on a glass slide. As with the pollen and charcoal analyses a Medilux 12 microscope was used but at a magnification of x1000 using oil immersion. Palaeoenvironmental interpretations are based on the major trends of relative abundances of the ecological groups (and not on the occurrence of different species) in a sample and therefore, as advocated by Vos & de Wolf (1993), the number of diatom frustules counted per sample has been restricted to 200 valves. The references used for identification were Cleve-Euler (1951-5), Hendey (1964), Hustedt (1927-62) and Krammer and Lange-Bertalot (1991). A complete species list is provided in Appendix B.

3.3.7 Pollen analysis and sea-level changes

Pollen grains are resistant to decay, abundantly produced, well dispersed and taxonomically relatively easy to identify - all characteristics that make pollen analysis the principal technique used to reconstruct Quaternary environments (Birks & Birks, 1980). The applications of palynology are numerous and have been well documented (e.g. Godwin 1975; Moore, Webb and Collinson, 1991; Lowe and Walker, 1996). The use of this technique for investigations of Late Devensian and Flandrian relative sea-level changes has also now become well established (e.g. Godwin, 1943; Brooks, 1972; Tooley 1978; Haggart 1982; Dawson and Smith, 1997).

Reconstruction of the local/regional vegetation history from the pollen assemblage at a site makes possible the identification of broad changes in the environment and sometimes local changes in marine influence. Additionally, the vegetation history of a site can be used as an independent relative dating method that can support radiometric dates. Pollen analysis can, to a certain degree, be used to identify breaks in sedimentation through changes in the pollen spectra. Some additional difficulties surrounding this technique in its application to sea level studies are outlined below.

3.3.8 Pollen: Laboratory Procedure

Samples for pollen analysis were selected in the laboratory. The sampling interval varied throughout the sedimentary sequence with the finest resolution (1cm intervals) concentrated across lithostratigraphical boundaries. In all cases either 2g or 1g wet weight of sediment (never more than 0.5cm width in the core) was taken at each level. Chemical preparation of the sample followed procedures outlined in Barber (1976). Hydrofluoric acid (HF) was only used on those sediments with a visible minerogenic content. *Lycopodium* tablets were added to the sediment prior to chemical preparation for the purposes of calculating pollen and charred particle concentrations (see section 3.3.9) where appropriate (Stockmarr, 1971).

Rather than counting every pollen grain in each level (which can sometimes reach tens of thousands) it is necessary to restrict the number of grains counted per sample. Dimbleby (1957) discussed the total number of pollen grains that ought to be counted to achieve a representative picture of the pollen in the sample. In laboratory tests he established that all those taxa which have a final percentage value in excess of 1% of all pollen were identified within the first 250 grains. However, it was acknowledged that if one taxon were to dominate a sample then in excess of 250 grains should be counted to ensure that all major taxa are identified. Berglund & Ralska-Jasiewiczowa

(1986) indicate that 500 tree pollen should be counted in forested areas and 500 tree and non-tree pollen in open areas. An increase to 1000 or even 2000 pollen per sample is further suggested when dealing with human-influenced landscapes so that important but rare indicator species are represented in sufficient numbers. Birks & Birks (1980), who imply that a pollen count of between 300-500 per sample is adequate, have shown that a selected count may not be optimum for all pollen types. As Moore *et al.* (1991) point out, however, it is the nature of the question asked in the research project that should determine the size of the pollen count.

In the present study the role of pollen analysis is not to reconstruct a detailed vegetational history but to identify the nature of the environment across stratigraphic boundaries. Due to problems of species identification and taphonomic processes of pollen dispersal and deposition the existence of coastal/salt marsh species in the pollen record (e.g. *Plantago maritima*, *Salicornia*, Chenopodiaceae sp.) are not only hard to distinguish but their importance as indicators of local sea-level change is questionable (e.g. Chenopodiaceae species are common in many environments). An expansive, open and relatively flat environment such as an estuary has a large pollen catchment that undoubtedly includes a local and regional pollen spectra. In addition the transportation of grains by water (particularly saccate pollen grains) can be greatly enhanced with diurnal fluctuations in water level and river transport (e.g. pine pollen - see Mudie, 1982). Despite these problems attempts have been made to use pollen analysis as an indicator of sea level change through the absence or presence of salt marsh species and fluctuations in the representivity of saccate pollen grains (e.g. Traverse and Ginsberg, 1966; Carter *et al.*, 1993).

Jones (1988) outlines well the difficulties associated with differentiating between early human impact on the vegetation at a coastal site and natural vegetational changes during periods of sea-level fluctuations through pollen analysis. He further notes the likelihood of both factors operating at the same time due to the fertile and rich grazing lands provided by many coastal habitats. Therefore increasing the number of pollen counted per sample in order to identify these minor components is of little or no advantage. In addition to the above an experiment by the author was undertaken where selected samples were counted to 600 pollen grains with the numbers of each taxon recorded at intervals of 100. The results, converted to percentages, showed that the variations in representation of the main taxa were minimal at each stage. For these reasons the requirement to count more than 300 total land pollen (TLP) in this study was deemed negligible. Occasionally less than 300 pollen grains were counted in a sample when pollen concentration was low or pollen was poorly preserved.

All counts were undertaken using a Medilux 12 microscope at a magnification of x400. The pollen keys of Andrews (1984), Faegri and Iversen (1989) and Moore *et al.* (1991) were used in addition to the Coventry University Geography Department type slide collection.

3.3.9 Charred Particle analysis

The burning of biospheric material (e.g. wood) produces a high number of carbon (charred) particles, which after being deposited can in favorable conditions be preserved in sediments throughout geological periods (Tolonen, 1986). Identification and quantitative analysis of these charred particles in minerogenic or biogenic deposits can assist in tracing the history of air pollution, forest fires and consequently can be used as an effective indicator of increased human activity (Tolonen, *op cit.*). With the impact of sea level changes on vegetation similar to those of anthropogenic activity this technique has been applied at Brighouse Bay (borehole T42) where the cause of these changes is uncertain.

Although a number of charred particle methods have been developed the point-count estimation technique, outlined by Clark (1982) and described below, has been employed in this study. This particular technique is relatively rapid, provides an objective estimate of charcoal content and the sampling and chemical preparation procedure is the same as for pollen (Robinson, 1984).

All counts were undertaken using a Medilux 12 microscope at a magnification of x100. The counting procedure involved using a 100 square grid which is moved across the slide one grid length at a time until five complete transects had been completed. For each level the number of grids, *Lycopodium* spores within each grid and the charred particles that fell on an intersection point of the grid squares were recorded. From this the concentration of charcoal at each level was calculated (for equation see Clark, 1982).

3.3.10 Presentation of results and zonation criteria

The results from all the palaeoenvironmental investigations in this study have been presented, where appropriate, as population diagrams using Tilia 1.08/Tilia.graph 1.16 (Grimm, 1991). The results of the foraminifera, ostracod and mollusc analyses are presented in total numbers, the pollen data are presented as percentages of TLP (i.e. excluding spores and aquatics which are expressed as percentages of TLP) and diatom data are presented as percentages of total populations. Zonation of the pollen data from Brighouse Bay (borehole T42) uses the statistical technique of CONISS (Stratigraphically constrained cluster analysis using sum of squares and Euclidean squared distances) in combination with a visual assessment of the data to identify Local Pollen Assemblage Zones (LPAZs). Where appropriate, all other diagrams have been zoned visually based on either changing population structures or changing species abundances. Due to the variability in population numbers of foraminifera and ostracoda some zones are based on samples that contain few or no tests/valves respectively. It is acknowledged that in this circumstance a "zone" can not be regarded as such. This criteria is, however, believed to be justified by the modern analogue survey (Chapter 4) where specific intertidal environments (e.g. high saltings terrace) are characterised by the absence of species. In preference to the term "zone", therefore, in this study all fossil faunal data will be divided into "phases" where fluctuating abundances and absence of animals are considered feasible criteria for the division of the data. In addition this approach is also very convenient for the presentation and description of the results.

3.3.11 Particle size analysis

In this study analysis of particle size composition was adopted as a scientific means of describing and studying the physical properties of the fine grained coastal sediments. The use of this technique in studies of relative sea-level change or coastal evolution is rare (e.g. Shi, 1994) although its application in combination with palaeoecological reconstructions of fossil intertidal marsh sediments has been attempted (e.g. de Rijk, 1995). In the latter study de Rijk (1995) recorded that the inorganic fraction of the intertidal "marsh" sediments were comprised mainly of silts (*circa* 80%) and consistent (*circa* 10%) amounts of clay but with a highly variable amount of sand ranging from *circa* 2%-35%. No explanation for this variability of sand content was provided but clearly was regarded as being of significance (see Figures 6.8 and 6.9 in de Rijk, 1995). Particle size analysis, therefore, complements microfaunal reconstructions of fossil estuarine sediments.

Particle size distributions were determined using a Malvern laser granulometer; a measurement system which is based on the principle that particles of a given size diffract light through a given angle, the angle increasing with decreasing particle size (McCave and Syvitski, 1991). The size distributions of the sediment classes of clay, silt and sand are respectively . Samples (0.1-0.5g wet weight) were taken from both the modern and fossil sediments. The sampling interval of the fossil estuarine sediments from CWF/A varied between 5cm and 20cm where a 5mm wide spatula scoop of the sediment was taken. Where the organic content of the sediments was high, either visibly or through anomalous particle size results, the samples were pre-treated in a 30% Hydrogen peroxide solution at room temperature until a reaction had ceased. All samples were introduced into the mixing cell of the granulometer and dispersed in water using ultra-sound energy. After approximately 1.5 minutes ultra-sound was found to degrade the sample and for this reason repeat measurements of such samples were not made.

Analysis was undertaken by Mrs L. K. Holloway (Centre for Quaternary Science, Coventry University) on the modern (intertidal) analogue samples (Chapter 4) and the fossil sediments of the sampled borehole CWF/A (Chapter 7). The particle size data is presented diagramatically in the following forms; a) as stacked percentage frequency histograms (according to Shi, 1994), b) as percentages of clay (<2μm), silt (2-63μm) and sand (>63 μm), and c) as mean and modal grain size (μm). The results have not been "zoned" or "phased" in this thesis.

3.4 Constructing a regional age-altitude relative sea-level graph

3.4.1 Introduction

It is not only common practice in Late Quaternary relative sea-level investigations but necessary to present evidence for former patterns of relative sea-level change in an age-altitude graph so that inter-regional correlations and comparisons can be made. The index points used in the construction of such a graph should have five attributes: a location; an age; an altitude; an indicative meaning; and a reference water level (for definitions of these terms see below) (Scaife and Long, 1994). During the early development of regional relative sea-level studies index points were commonly presented as point plots on a graph with no error margins applied (e.g. Jardine, 1975a; Tooley, 1978). The result would be a best fit line joining the index points together to form a sea-level curve. Frequently intercalated marine and freshwater sediments were considered to represent oscillations in sea-level resulting in a complex set of variations in the sea-level curve (e.g. Tooley, 1978; Devoy, 1979). In contrast, other investigators (e.g. Kidson and Heyworth, 1978) considered the oscillations of sea-level implied by lithostratigraphic evidence to be smaller than the potential errors in the reconstruction of former sea levels and thus produced a smoothly rising sea-level graph (Scaife and Long, 1994).

The misleadingly precise graphs produced up to and throughout the 1970's (including those mentioned above) have been superseded by an approach that acknowledges the errors and deficiencies of the data base (Shennan, 1986b). The requirement to incorporate margins of error has been suggested (Shennan, 1982) so that index points are presented within error boxes and a sea-level band (as opposed to the single line curve) is used that incorporates all sea-level index points (e.g. Devoy, 1982). Heyworth and Kidson (1982) modified the error box approach, instead using error ellipses. They acknowledged that altitudinal errors existed but believed that they could not be statistically calculated with the same accuracy as the standard deviations applied to radiocarbon dates.

Jardine (1975b) realised the need to correct index points to a mean tide level using present tide gauge information so that inter-regional correlations could be made between areas with markedly different modern and palaeo- tidal ranges. This requirement did not filter immediately into the construction of age-altitude sea-level graphs (e.g. Devoy, 1982; Heyworth and Kidson, 1982). More recently a review of relative sea-level curves for Scotland has attempted to standardise these for accurate comparison (Haggart, 1989). From this exercise Haggart (*op. cit.*) concluded that compatible methodologies were still not being employed in the construction of relative sea-level curves thus denying the possibilities of inter-regional comparison with any degree of accuracy.

Perhaps the most systematic attempt to develop the raw data of a sea-level index point into an age/altitude graph was undertaken for the Netherlands contribution to the IGCP Project 61(van de Plassche, 1982). For this a twelve step approach was applied to deriving a relative sea-level curve from fossil indicators and has been summarised in Figure 3.1. The first two steps require the investigator to consider both the indicative meaning of the data by establishing a relationship to a former tidal level and also to evaluate the former local tidal range. Steps 3 to 7 consider altitudinal accuracy of the fossil indicator including whether it is *in situ* and estimating the potential degree of sediment compaction - particularly of both peat and clay. Having followed the first 7 steps in this procedure the vertical (altitudinal) margin of error should be established. Steps 8 to 12 consider the problems of establishing an age for the fossil indicator including reliability of dateable material, the errors associated with radiocarbon dating (see section 3.4.7) and the conversion of the date to a calibrated timescale - in this way the horizontal (age) margin of error can be calculated (van de Plassche, *op cit.*).

Relative sea-level index point determination in the present research has applied this approach to evaluating the potential error margins involved. Lithostratigraphical surveying (Chapters 5 and 6) provides the necessary context for the sea-level investigation and through stratigraphical correlation indicates the degree of sediment compaction since deposition. Modern analogues (Chapter 4) are utilised to evaluate the former tidal levels indicated by the fossil evidence (Chapter 5 and 7). Quantitative and qualitative population age structures of the fossil fauna are determined to establish the autochthonous nature of the assemblage (Chapters 5 and 7). Palynological investigations have been undertaken primarily to establish the suitability of the dateable material (Chapter 8) by evaluating the probability that continuity of sedimentation exists over regressive/transgressive sea-level boundaries. The following sections not only define the main terms and concepts associated with determining sea-level index points but also consider the major sources of error in both age and altitude encountered in this process.

3.4.2 Reference water-level relationship and indicative meaning

The indicative meaning of a dated sample is the relationship of the immediate environment in which it accumulated to a reference tide level (Shennan, 1986). Van de Plassche (1986) noted that 'coastal' features may have a more precise, site dependent, and a less precise, vertical relationship to one or other local average sea level - known as the *reference water-level relationship*. Further, the reference water-level relationship of physical, biological and other features originating in coastal areas imply that they possess an indicative meaning with respect to present-day or former average sea level or a tide level-related groundwater level position - hence the term sea level indicator (van de Plassche, 1986). In macrotidal areas (e.g. the Solway Firth) an assessment of the correct indicative meaning for a sample is more important than in microtidal areas (Shennan, *op cit.*).

The concept of an indicative meaning of a sea-level index point has been developed (van de Plassche, 1982) to distinguish stratigraphic changes - recorded as regressive or transgressive onlaps (Shennan, 1983) - from the interpretation of a sedimentary sequence. Only by comparing all lines of evidence associated with a sea-level index point (including lithostratigraphical and biostratigraphical evidence) is it possible to interpret the indicative meaning of that data point in terms of the dominant tendency (positive or negative) of sea-level movement (Shennan, 1983). Shennan (1986) stresses four main points concerning the indicative meaning and range of sea level index points:

a) the indicative meaning is dependent on the type of stratigraphic overlap under consideration,

b) the reference water level for each type of indicator should be given as a mathematical expression of tidal parameters (e.g. the mid-point between mean high water of spring tides, MHWST, and the highest astronomical tide, HAT) rather than a single tide level ± a constant factor (e.g. MHWST + 80 cm) since the constant factor will indicate quite different tidal inundation characteristics for areas of different tidal range,

c) the indicative range can be reduced by dating the level at which the pollen, diatom, macrofossil and stratigraphic evidence reveal a change in the sedimentary environment, therefore dated samples from the middle of homogenous peat layers are less useful, and

d) the accuracy of reference tide levels must be assessed.

It should not be assumed that a transgressive or regressive overlap equates automatically to positive or negative tendencies in sea-level movement respectively (Shennan, *op cit.*). Shennan *et al.* (1983) have applied this approach by plotting each index point as either a positive or negative tendency against its age range. The production of local sea-level tendency graphs thus allows for the simplified and clearer identification of the broader picture of relative sea-level movements that is independent of altitude constraints and inaccuracies (e.g. Long, 1992). This method has provided a basis for inter-regional correlations between areas of differing environmental and crustal histories.

3.4.3 Potential sources of altitudinal error

The process of establishing a precise altitude for a relative sea-level index point is complicated by the numerous potential inaccuracies encountered not only as a result of post-depositional alterations in sediment elevation (i.e. compaction; Jelgersma, 1961) but also human errors during site investigations and sample recovery. Scaife and Long (1994) considered that when all factors are taken into account when determining a sea-level index point then a transgressive or regressive contact will have a typical altitudinal uncertainty of *circa* ±0.50m. Gehrels *et al.* (1996) most recently have attempted to estimate more systematically the size of error associated with a number of the main sources where potential inaccuracies occur. Using this approach the minimum cumulative error was estimated to be as low as ±0.13m. However, in most cases the total error was estimated as high as ±0.30-0.50m for mean tide level chronologies (i.e. where each index point is corrected to a local mean tide level).

The inconsistencies of the above estimates of altitudinal error show clearly the difficulties in quantifying errors to particular variables. The following sections attempt to outline and discuss the main sources of altitudinal errors in sea level studies including definitions of common terminology and estimations (where possible) of those error values.

3.4.4 Measurement errors

Inherent in any investigation are errors that arise from the human factor. In sea level studies these errors are commonly related to altitude measurement. Shennan (1986b, 1980) suggested that these errors may arise at three stages of measurement: during the measurement of depth in a borehole, during leveling of the site to Ordnance Survey benchmarks, and finally with the assessment of the benchmark's accuracy to O.D. Newlyn. Of the latter two stages Shennan (1986b) estimated that for local comparisons benchmarks are accurate to ±0.01m. However, for inter-regional comparisons (British Isles) the error is closer to ±0.15m for England and Wales and ±0.20m for Scotland relative to O.D. (Shennan, *op cit.*).

The errors associated with the measurement of depth in a borehole have recently been estimated as ±0.03m (Gehrels *et al.*, 1996). In addition Gehrels *et al.* (*op cit.*) estimated values for errors associated with compaction during vibrocoring (±0.01m) and the angle of a borehole (±0.02m) - by their own admission these values represent best guesses rather than statistically determined values. Elsewhere instrumental leveling errors have been evaluated as being in the region of ±0.011m (Sutherland, 1983).

3.4.5 Palaeo-tidal levels

In addition to the problems of defining the relationship between an index point and a former local tidal position there is a probability that a very different palaeotidal regime existed at locations (particularly those with a large tidal range) where the coastal configuration has altered significantly over time (Jardine, 1975b). In addition, the complexity of many coastal environments with beach-barrier lagoons, reefs or offshore sedimentary structures, resulting in the restriction of marine access causing tidal changes on the coastline, may lead to the incorrect interpretation of isolated index points (Devoy, 1987). Tooley (1978) considered that it would only be possible to compute the tidal range of former inlets and bays if their geometry can be established for different times during the Flandrian. An attempt to model the former geometry of the Wash in eastern England and estimate the former tidal regime during the Flandrian has been undertaken (Hinton, 1992). Hinton (*op cit.*) suggested that palaeo-tidal ranges in this area were at variance with the present day and that the differences in height of the sea-level index points broadly correspond to these variations.

The scope of the present study does not allow for the accurate modeling of the former geometry of the Cree estuary region throughout the Flandrian. Therefore tidal range in this area is taken to have been constant over the last *circa* 10,000 years. All relative sea-level index points determined in this study are, in accord with Jardine (1975b), corrected to a former Mean Tide Level based on present tidal levels in the Cree estuary region (see Table 4.1 in Chapter 4). In this way it will be possible to make inter-regional comparisons of the relative sea level data more accurately between areas that have markedly different tidal regimes (e.g. Haggart, 1989). This issue is clearly demonstrated in Figure 3.2 where the differential (H) of the value of a Mean High Water of Spring Tides between micro-, meso- or macro-tidal areas is far greater than that (h) of a Mean Tide Level from each location.

3.4.6 Compaction and consolidation of sediments

Some sea-level researchers have acknowledged the problems of compaction and consolidation of sediments but have chosen not to incorporate an altitudinal correction factor to the data (e.g. Tooley, 1978; Devoy, 1978 ; Haggart, 1982; Firth and Haggart, 1989). Undoubtedly until more accurate methods of determining compaction and consolidation of coastal sediments are available all assessments of altitudinal variation should be regarded as approximate (Greensmith and Tucker, 1986). It is common practice to incorporate an error of altitude related to the compaction and consolidation of sediments in relative sea-level studies and in the construction of age/altitude graphs (e.g. Kidson and Heyworth, 1973; Cullingford *et al.*, 1980; Long, 1992).

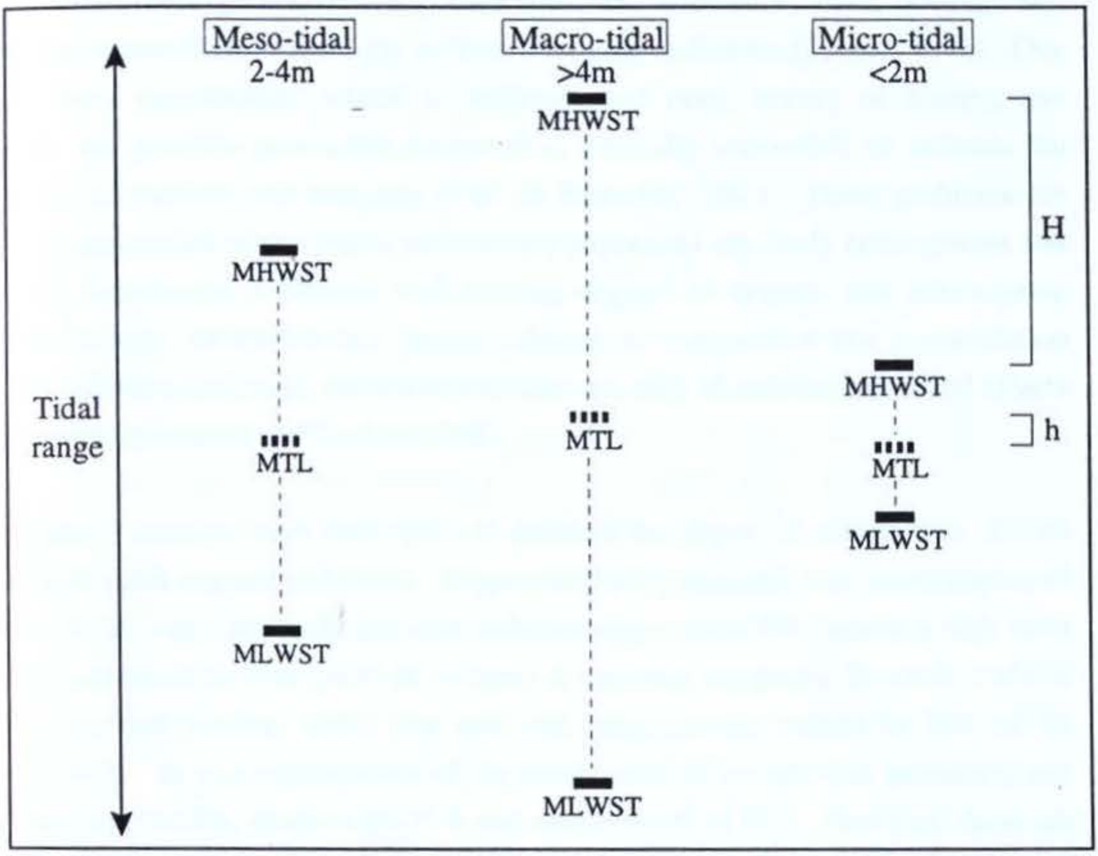


Figure 3.2 Comparison between three idealised locations of micro-, meso- and macro-tidal ranges. The tide levels shown are Mean High Water of Spring Tides (MHWST), Mean Tide Level (MTL) and Mean Low Water of Spring Tides (MLWST). The values H and h represent the difference in altitude of the MHWST mark and the MTL mark respectively between the three locations.

Flandrian coastal deposits are commonly comprised of deep sequences of unconsolidated sediments. The determination of the original height of sediments relating to a former sea-level is thus complicated due to autocompaction of peats and the compaction and consolidation of associated sediments (Kaye and Barghoorn, 1964; Sutherland, 1983). The extent of this problem is exemplified by Jelgersma's study of the lagoonal areas of the Netherlands where these effects have been so irregular that data from this area cannot be used for sea-level change studies (Jelgersma, 1961).

All sediments undergo consolidation over time also affected by time, drainage and load, either under their own weight or from overlying sediments (Tooley, 1978). Due to the many uncertainties related to sedimentation rates, history of loading and aeration, and possible pore-water escape, it is generally impossible to estimate the effect of compaction with accuracy (Van de Plassche, 1982). These problems are further compounded when coastal sedimentary sequences are rarely homogenous and comprise intercalated sediments with varying degrees of organic and minerogenic content (Tooley, 1978). Further factors relevant to compaction and consolidation include sediment thickness, variability and discontinuity of sedimentation and effects of loading (Greensmith and Tucker, 1986).

A number of attempts have been made to estimate the degree of compaction of both minerogenic and organic sediments. Jelgersma (1961) recorded that consolidation of deposits could vary markedly between sediment types from 0% (where a high sand fraction is present) to 90% (peat) of volume. It has been suggested (Boswell, 1961 in Greensmith and Tucker, 1986) that peat can progressively reduce to 10% of its original thickness as a consequence of the continuance of compaction processes, and clay muds to 11-25%, sands to 66-75% and calcite muds to 50%. However, these are maximum figures unlikely to be attained in coastal situations over a geologically short period of several thousand years (Greensmith and Tucker, 1986). In the case of peat there is initially a very rapid compaction (*primary consolidation*) when a load is applied accounting up to 50% of total settlement in a relatively short space of time (MacFarlane, 1965). Over the longer term (*secondary consolidation*) further compaction occurs (MacFarlane, *op cit.*) which is thought to be linear with log-time (Barden, 1968).

One procedure sometimes followed in sea-level studies is to relate the age of a sample from the base of a peat bed, that has been lowered due to compaction of underlying deposits, to the altitude of the bed where it is found to rest on non- or much less compactable deposits (Van de Plassche, 1982). Van de Plassche (*op cit.*) suggests caution using this approach due to assumptions inherent in the procedure and the ease of which considerable errors can be attained in the calculations. In contrast Cullingford *et al.* (1980) considered the compaction of peat for the sea-level index points from Lower Strathearn (Scotland). They noted that the compaction of the sandy sub-peat materials was negligible. The estimated values for compaction at the three sites ranged between 40 and 68% - where no measurements had been taken an overall mean value of 52% compaction was applied to each peat surface height (Cullingford *et al.*, *op cit.*).

In this study peat compaction is calculated using the maximal value (68%) as estimated by Cullingford *et al.* (1980). The compaction and consolidation of silts and clays has not been quantitatively calculated but where inconsistencies in stratigraphic relationships exist a qualitative assessment of compaction is provided and discussed in the appropriate section.

3.4.7 Radiocarbon Dating and sea-level changes

The ubiquitous distribution of ^{14}C has allowed radiocarbon dating to become the primary dating method for palaeoecology and archaeology during the Late Quaternary. All aspects of this technique have been detailed on numerous occasions (e.g. Libby, 1965; Bowen, 1978; Lowe & Walker, 1984; Bradley, 1985; Pilcher, 1991). Absolute dating techniques are now an essential part of sea-level studies with the construction of a regional sea-level curve dependent on them (see Haggart, 1989). The nature of all study sites in the present investigation - with intercalated minerogenic and biogenic sediments - lends itself to the application of radiocarbon dating.

Both Tooley (1978) and Sutherland (1983) have reviewed the potential sources of error (with particular reference to sea-level studies) associated with radiocarbon dating techniques. As many deposits are heterogenous peat or organic rich sediments can be made up of short lived plants (e.g. mosses), the remains of older components and the roots of younger plants that will have penetrated the sediment from above (Olsson, 1986). Marine organisms pose a separate problem where, due to ocean surface water (where ^{14}C activity is *circa* 5% less than that of the atmosphere) mixing with deep low radiocarbon ocean water, apparent ages can be hundreds or even thousands of years older than their true ages (Bradley, 1985). These problems are further exacerbated in the brackish water environment where an additional hard-water affect may increase the errors of a radiocarbon date (Pilcher, 1991). In the present study two radiocarbon dates have been acquired on marine shell samples. To account for this "old carbon" factor a correction age value of 425 ^{14}C years (calculated from the modern marine shell radiocarbon dates from northern Britain - see Figure 1 in Sutherland, 1983) has been subtracted from the conventional radiocarbon age.

More worrying is the realisation that non-constant atmospheric ^{14}C levels existed during the past (e.g. Stuiver *et al.*, 1991) due to variations in cosmic rays reaching the Earth. Pilcher (1991) reviews this fundamental problem in the dating technique and notes that the only way of providing a correction factor for the variations in the past is to make an empirical calibration. Using dendrochronology in combination with high precision radiocarbon dating methods calibration curves that span the Flandrian and possibly further back in time are being developed (Stuiver *et al.*, 1986, 1991; Stuiver & Pearson, 1992). The implications of this are that a single radiocarbon date, when calibrated, can represent a number of possible dates over wide time periods (hundreds of years) - commonly referred to as *radiocarbon plateaux* (Pearson and Stuiver, 1986). One such example of this phenomenon occurs between *circa* 9,500 and 9,700 ^{14}C years BP and is shown in Figure 3.3 (from Kromer *et al.*, 1995).

Despite the many sources of error associated with radiocarbon dating, in association with the relative dating provided by pollen analysis, it remains the most appropriate and accurate absolute dating method in the present research. In most cases peat deposits with a high organic content have been sent for standard radiocarbon dating, although, where appropriate, (i.e. for small samples and/or shell samples) the alternative and essentially more accurate (Pilcher, 1991) Accelerator Mass Spectometry (AMS) radiocarbon technique has been employed. This is a method in which the ^{14}C atoms are separated by their difference in mass rather than by their radioactivity. Although considerably more expensive than the conventional method of radiocarbon dating this system can measure samples as small as 0.2mg - an advantage that has allowed for the establishment of chronologies on otherwise undateable deposits (Pilcher, *op cit.*).

Each sample sent for radiocarbon dating was extracted in the laboratory taking care not to contaminate the sediment from above or below by removing any traces of core smearing, rootlet penetration and any possible allochthonous material. All shell samples were washed carefully in distilled water, dried and only single-species samples were sent for dating. All samples sent for standard radiocarbon dates were undertaken by Beta Analytic Inc., Miami, USA. All samples sent for AMS dates were also undertaken by Beta Analytic Inc. but were sub-contracted to Lawrence Livermore

National Laboratory (California, USA). Once measured, details of all samples were returned, providing information on sample pretreatment, measured radiocarbon age, $^{13}C/^{12}C$ ratio, conventional ^{14}C age and calibrated ages based on the Pretoria Calibration Procedure program (see Vogel *et al.*, 1993).

3.4.8 Details of radiocarbon dated relative sea-level index points

All samples that were radiocarbon dated in the present study have been catalogued in tabular form in the appropriate sections. Each radiocarbon dated index point has been evaluated for application as a relative sea-level indicator using the results of the lithostratigraphical and biostratigraphical investigations. The details provided for each radiocarbon dated sea-level index point is as follows: Site/borehole code; Grid-reference; Laboratory code; ^{14}C date (^{14}C years BP); Material; Age in calibrated years BP (2 sigma); Altitude (metres OD); Indicative meaning; Mean Tide Level correction factor (based on contemporary tidal range values - see Chapter 4); Altitudinal error range; Stratigraphical environment; Sea-level tendency.

3.5 Conclusion

In the following chapters the application of each palaeoecological technique will not adhere to a rigid methodology. Through the sequences of estuarine and marl sediments the detail of environmental reconstruction provided by foraminifera, ostracod and mollusc analyses was unrivaled. However, over important minerogenic/biogenic boundaries pollen and, where present, diatom analyses have proven to be the most effective techniques in determining continuity of sedimentation. As has been shown from similar studies (e.g. Haynes *et al.*, 1977; Prince, 1988; Brew *et al.*, 1992) by taking a flexible, multidisciplinary approach to the problems of relative sea-level changes and coastal evolution it is considered that a more precise and complete picture of these changes has been achieved.

The principle of palaeoecological reconstruction is, however, based upon an understanding of modern analogues. The distribution of modern foraminifera and ostracoda in Scottish estuaries has not been studied in any detail since the last century (Brady and Robertson, 1870). Thus prior to the palaeoenvironmental investigations of the fossil sediments in the Cree estuary region an investigation of contemporary coastal depositional environments and associated assemblages in this area was undertaken (Chapter 4).

Chapter 4 Modern analogues

4.1 Introduction

The ability to relate palaeoenvironmental data from fossil marine deposits to modern analogues is of primary importance in both the reconstruction of former relative sea levels and the development of a model of coastal/estuarine evolution. In this thesis foraminifera and ostracoda have been employed as the primary palaeoecological tools for reconstructing sea-level changes and coastal evolution. Of these two microfaunal groups foraminifera, compared to ostracoda, are commonly more abundant and diverse in estuarine environments. This factor has inevitably resulted in the use of foraminifera analysis as the main technique used here for palaeoenvironmental reconstruction in estuarine and brackish water fossil deposits overshadowing the use of ostracods for this task (e.g. Boomer and Godwin, 1993). In a previous study qualitative investigations of the carse deposits of the Solway Firth identified both fossilised foraminifera and ostracoda - the results of which were used to supplement the relative sea-level change research of Jardine (1975). To date, however, no systematic survey of the modern and/or fossil estuarine sediments of the Cree estuary nor of the Solway Firth for foraminifera and ostracoda has been undertaken.

Distribution studies of both microfossil types in the British Isles has lacked a positive link between distinctive biozones and present tidal levels. Such a connection is crucial if the microfossil content of fossil marine sediments are to be used to their full potential in reconstructing former relative sea-levels. The studies of researchers in the USA, most notably Scott and Medioli (1986), have paved the way in this area of research. It is hoped that the following investigation may be able to make similar advancements in the use of foraminifera and ostracoda for understanding relative sea-level changes.

Presented here are the results of an investigation of surface sediment samples taken from a number of modern intertidal depositional environments. Each sample has been analysed for foraminifera and ostracods with additional information provided from diatom (Analysis: Miss A. De la Vega) and particle size (Analysis: Mrs L. Holloway) analyses.

The structure of this chapter is as follows. Firstly, details of the tide levels for the northern shoreline of the Solway Firth are provided in order that each sampled location can be related directly to a present tide level. Also detailed is an altitude range for the most conspicuous of all the sedimentary facies of the Cree estuary. These are the relatively horizontal vegetated terraces - referred to here as the "saltings" - that flank the intertidal mudflats. In the final sections of this chapter are presented the results of the modern survey undertaken in this study and an attempt is made to establish some biozones for the Cree estuary region.

4.1.1 Tidal data for the western Solway Firth

In this study the Admiralty Tide Tables (1996) have been used for calculating tidal data for the western Solway Firth. In Table 4.1 are details of 8 secondary ports within this region for which levels relative to O.D. for Mean High Water of Spring Tides (MHWST), Mean High Water of Neap Tides (MHWNT), Mean Tide Level (MTL), Mean Low Water of Neap Tides (MLWNT) and Mean Low Water of Spring Tides (MLWST) were available. Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT) values were extrapolated from the given data where possible and M^1 was calculated using the equation (HAT + MHWST)/2 in accord with Shennan (1986b). For both the Cree estuary (Chapters 6, 7 and 8) and Brighouse Bay (Chapter 5) the Kirkcudbright Bay tide values have been employed which provides the closest and most analogous coastal situation to both locations. For the West Preston (Appendix A) site the Hestan Islet tide station figures are used.

[Note: not all ports or figures are utilised in this study but are included for regional comparison]

4.1.2 Altitude of the saltings/merse terrace

The highest altitude to which the tide reaches (taken here to equate to MHWST) is marked by the presence of the vegetated saltings. In the present study altitudes for this feature at five separate locations in the Cree Estuary have been recorded (Table 4.2).

The saltings closest to the mouth of the estuary at Carsewalloch Flow record a small altitudinal range between 4.05-4.18 m O.D. and a mean altitude of 4.11m O.D.. The other four locations at Carse of Barr, Nether Barr and at Machermore are all positioned within 2 km of the furthest extent (upstream) of the Cree estuary. Within these sections the saltings surface ranges in altitude between 4.12-4.50 m O.D. For the purposes of this study the total range of the saltings that flank the Cree estuary is therefore taken as being from 4.05-4.50m O.D..

Table 4.1 Tide levels for Dumfries and Galloway

Levels relative to O.D., in metres (source: Admiralty Tide Tables, 1996)

Secondary Port	HAT*	M[1]	MHWST	MHWNT	MTL	MLWNT	MLWST	LAT*
Stranraer	2.2	1.90	1.6	1.0	0.12	-0.8	-1.3	-1.9
Portpatrick	3.1	2.55	2.0	1.2	0.20	-0.9	-1.5	-2.5
Drummore	3.9	3.35	2.8	1.8	0.25	-1.1	-2.5	-3.5
Port William	3.9	3.35	2.8	1.6	-	-1.5	-	-
Isle of Whithorn	4.2	3.65	3.1	1.6	0.00	-1.7	-3.1	-4.1
Garlieston	4.3	3.75	3.2	1.9	-	-1.4	-	-
Kirkcudbright Bay	4.9	4.35	3.8	2.2	0.45	-1.3	-2.9	-3.9
Hestan Islet	5.4	4.85	4.3	2.3	0.47	-1.6	-3.1	-4.1

* extrapolated values

\- incomplete data

$M^1 = (HAT + MHWST)/2$

Table 4.2 Altitudes of the Cree estuary merse (saltings) at five locations including the margins of error associated with each site. By accumulating the data from each location values for the Cree estuary are also provided.

Location	Mean (NX) grid reference	Number of points	Altitude Range (m O.D.)	Mean altitude (m O.D.)	Error margin
Carsewalloch Flow	4613 6093	6	4.05 - 4.18	4.11	±0.13
Inks of Machermore	4207 6421	14	4.21 - 4.50	4.40	±0.29
Nether Barr	4240 6378	12	4.12 - 4.49	4.39	±0.37
Carse of Barr (1)	4337 6374	1	-	4.30	none
Carse of Barr (2)	4276 6384	4	4.35 - 4.50	4.44	±0.15
Cree estuary	**-**	**37**	**4.05 - 4.50**	**-**	**±0.45**

4.2 Limitations of the survey

The main objective of the surface sample survey was to identify diagnostic foraminifera and ostracoda faunas from inter-tidal environments in order to provide modern analogues for comparison with the assemblages identified in the fossil estuarine/brackish sediments of the Cree Estuary and Brighouse Bay. In a similar study (Scott and Medioli, 1980), which aimed to provide a modern foraminiferal analogue to aid palaeoecological interpretation, the need to differentiate the 'live' from the 'dead' population was not considered essential. Indeed it was suggested that treating these two populations together is more realistic for the interpretation of the fossil record. This approach has been criticised by Murray (1982) who believes that a truly representative survey must be based on both components of the population. Despite this his results show very clearly the striking relationship between the death and living assemblages. Consequently it was not deemed essential to separate the living from the death assemblages in this survey where the fossil assemblages would inevitably incorporate both components. It was not possible to take samples throughout the year from each site and consequently there is no consideration of seasonality in the microfaunal assemblages. Nor was it practicable to sample from any sub-tidal environments in the Cree estuary. A different problem was encountered at Brighouse Bay where no local analogue was available that would compare with the probable environment of deposition that resulted in the formation of the fossil marls. Thus the ecologies of all freshwater ostracod species rely on published work. It is hoped that these deficiencies do not overshadow the results of this investigation.

4.3 Sampling strategy

A number of locations were subsequently selected in the Cree estuary region for surface sampling. A series of samples were taken on a transect (for detail see Figure 4.1 - the general location of this area within the Cree estuary region is indicated in Figure 6.1) from the landward edge of the saltings to the edge of the Cree estuary channel (date of sampling: 21/4/1997). Each sample (10g wet weight) was taken to a depth of 1cm. The environments sampled were as follows: 1) landward edge of high saltmarsh; 2) unvegetated brackish pool in high marsh; 3) standing water in intertidal gully (end furthest from main channel); 4) high saltmarsh next to low saltmarsh; 5) standing water in intertidal gully (end closest to main channel); 6) low saltmarsh; 7) unvegetated brackish pool in low marsh (some seaweed present); 8) high intertidal channel mudflat and 9) low intertidal channel mudflat. Two additional samples were taken to supplement the study. One was taken from the extensive intertidal mudflats close to the open marine conditions of Wigtown Bay (sample 10) and another was

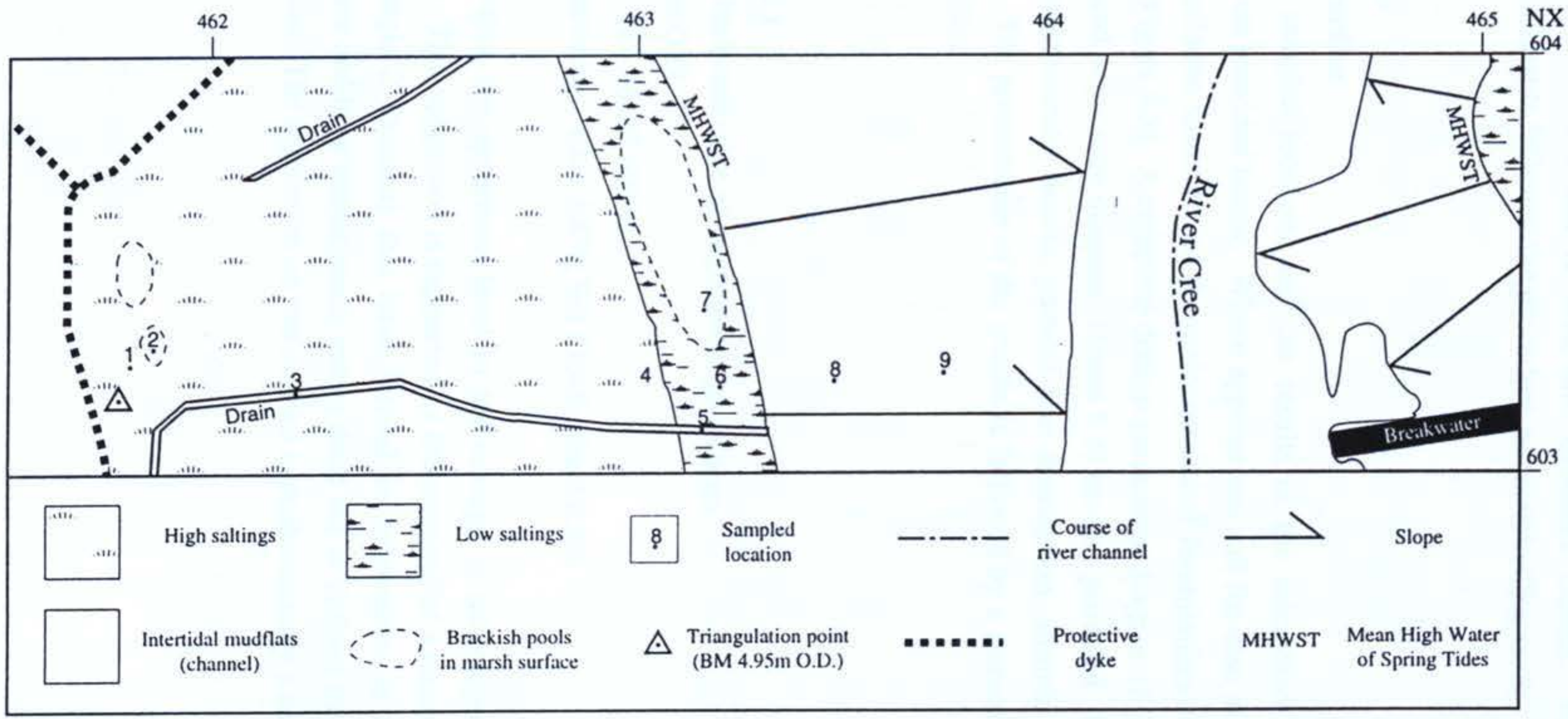


Figure 4.1 Location map of the samples taken for modern analogues in the Cree estuary

taken from the intertidal beach sands of Brighouse Bay (sample 11). All samples have been grid referenced and levelled into Ordnance Datum. Preparation and analysis of each sample followed the procedure outlined in Chapter 3.

4.4 Results

4.4.1 Introduction

Details of all sampled locations and the results of the microbiota and sediment investigations are provided below. Where appropriate, and for ease of interpretation, percentage population structures of the main species of foraminifera at each location are presented (Figure 4.2). A complete diatom percentage diagram (Figure 4.3) and a complete ostracod population diagram (Figure 4.4) are also provided. Listed for each location are environmental details, particle size distribution, altitude (m O.D.) and grid reference. The presentation of the results is followed by a summary of the main biozones identified.

4.4.2 Sample 1

Environment: landward edge of vegetated high saltings
Altitude: 4.02m O.D.
Grid reference: NX 46183 60326
Particle size percentage: Clay 1.8%; Silt 91.4%; Sand 6.8%

It is clear that this, the uppermost level in the saltings, is submerged on only the highest of tides. This suggestion is supported by the presence of a number of brackish pools (e.g. Sample 2 location) that have formed in depressions in this relatively horizontal surface and have subsequently either dried out or drained by seepage since the last inundation. The vegetation on this surface is predominantly a dense grass.

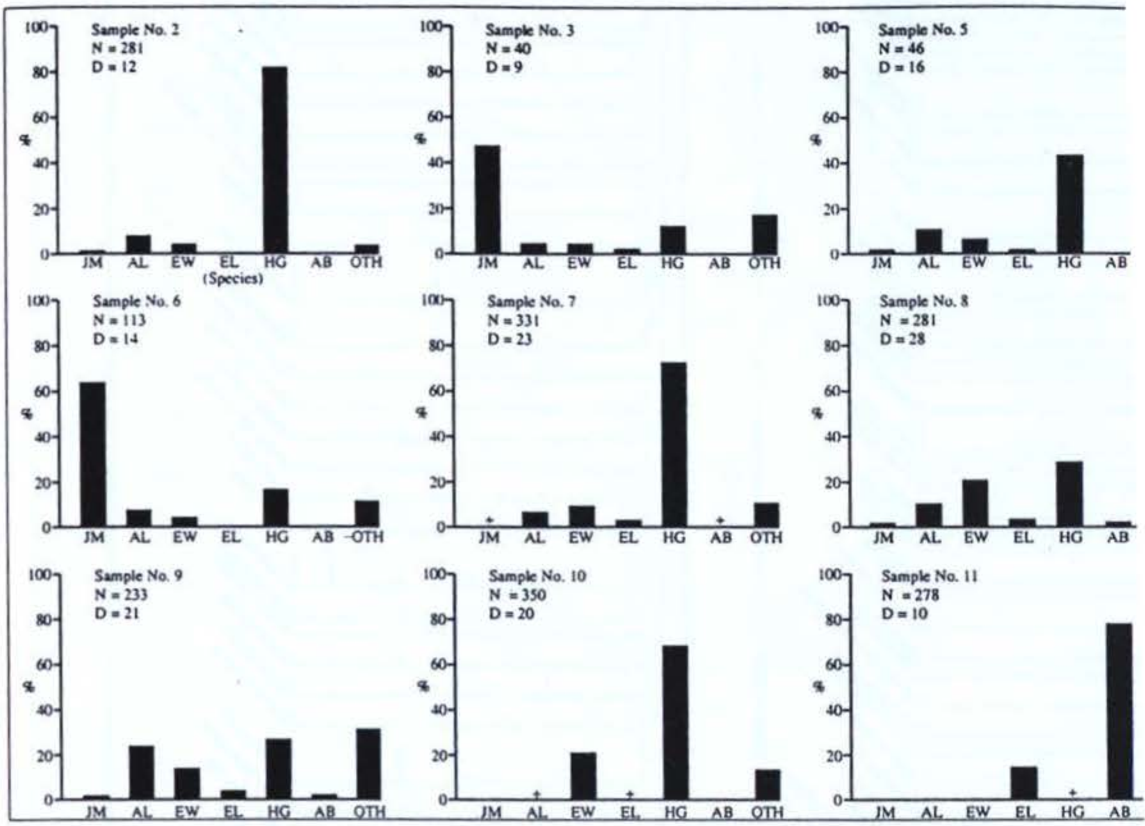
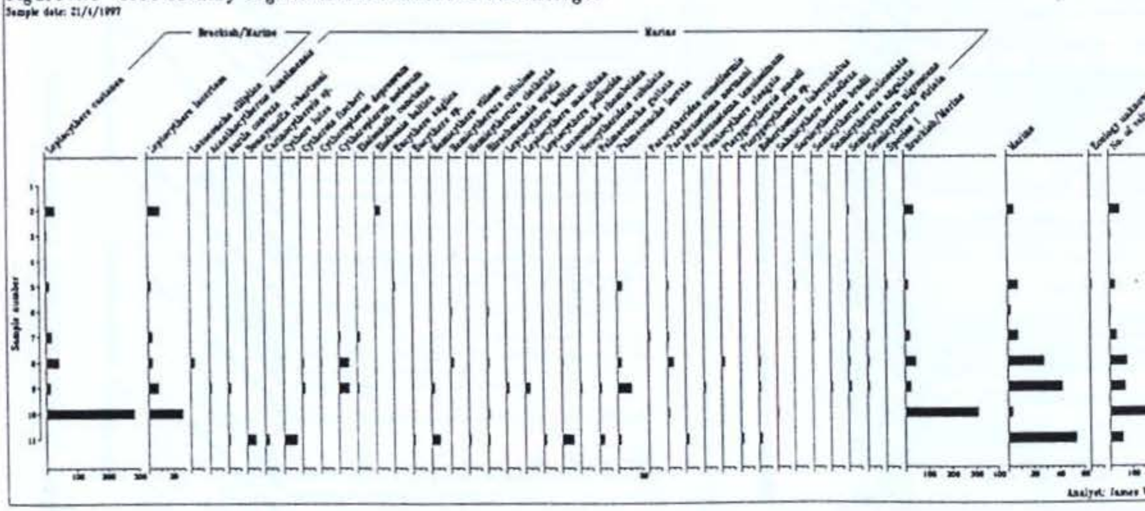
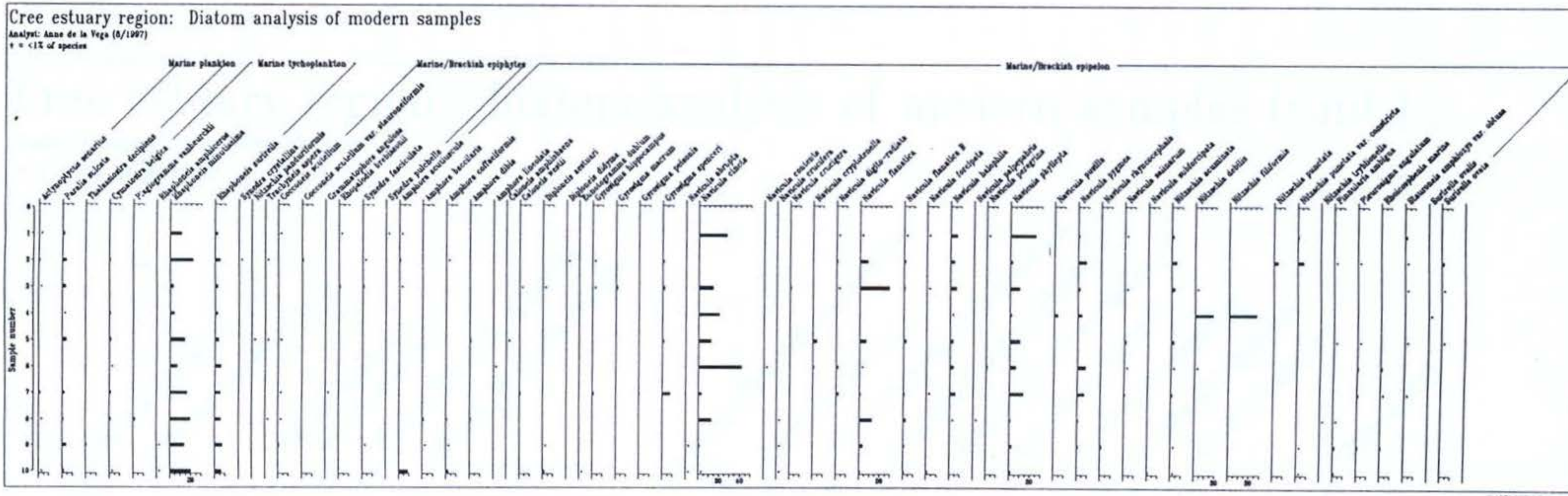
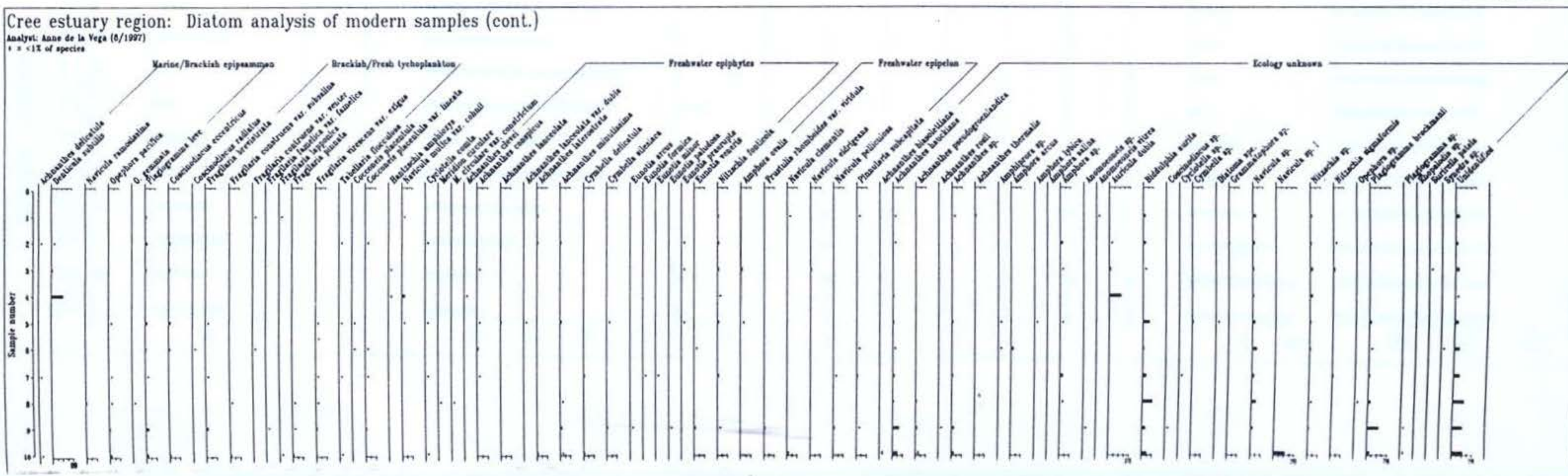


Figure 4.2 Foraminifera assemblage histograms from modern analogues. Each sample number relates tc depositional environment (see text for details). Foraminifera codes are : JM - *Jadammina macrescens*; A *Ammonia limnetes*; EW - *Elphidium williamsoni*; EL - *Elphidium exc.* f. *lidoensis*; HG - *Haynesina germanica*; AB - *Ammonia batavus*; OTH - Others; N = total number of tests; D - species diversity.

Figure 4.3 Cree estuary region: Modern ostracod assemblages

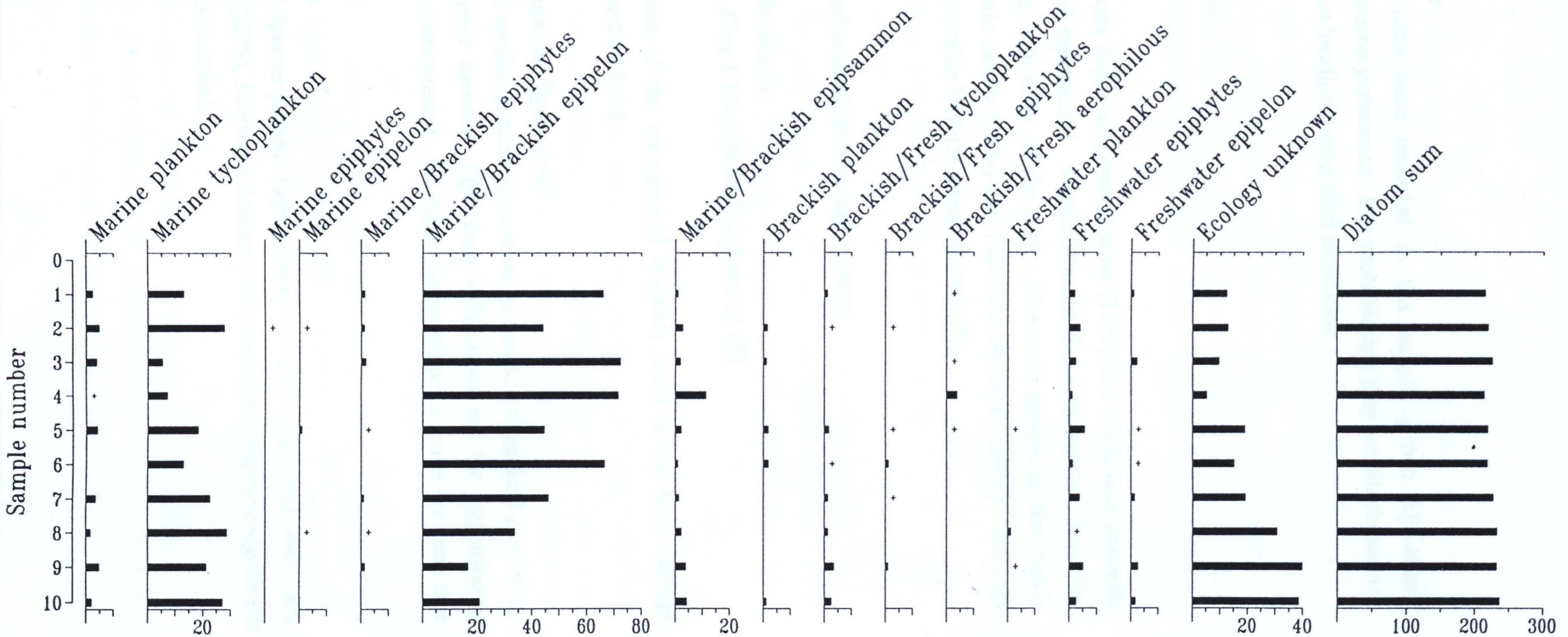



Cree estuary region: Diatom analysis of modern samples
Analyst: Anne de la Vega (8/1997)
+ = <1% of species
Marine plankton
Marine tychoplankton
Marine/Brackish epiphytes
Marine/Brackish epipelon
Sample number


Cree estuary region: Diatom analysis of modern samples (cont.)
Analyst: Anne de la Vega (8/1997)
+ = <1% of species
Marine/Brackish epipsammon
Brackish/Fresh tychoplankton
Freshwater epiphytes
Freshwater epipelon
Ecology unknown
Sample number

Cree estuary region: Diatom analysis of modern samples (cont.)

Analyst: Anne de la Vega (8/1997)
+ = <1% of species



Foraminifera assemblage

Only three foraminifera tests were recorded in this sample - two *Elphidium williamsoni* and one *Haynesina germanica*. It is probable that they are allochthonous and were transported to this location during tidal inundation.

Ostracod assemblage

No ostracods were recorded.

Diatom assemblage

The Marine Tychoplanktons *Raphoneis minutissima* (11%) and *Raphoneis surirella* (2%) make this group well represented. Marine/Brackish Epipelon species, however, dominate this assemblage with 66% of the total. The main species in this highly diverse group are *Navicula cincta* (26%) and *Navicula phyllepta* (24%). Ecology Unknown is at 12% and no other lifeform group exceeds 5%.

4.4.3 Sample 2

Environment: unvegetated brackish pool in high saltings

Altitude: 3.82m O.D.

Grid reference: NX 46186 60330

Particle size percentage: Clay 1.1%; Silt 86.3%; Sand 12.6%

The situation and location of the unvegetated brackish pools in the high saltings surface is mentioned in section 4.4.3.

Foraminifera assemblage (see figure 4.4a)

Of the 281 tests and 12 species present *Haynesina germanica* comprised over 80%. Low numbers of *Ammonia limnetes*, *Elphidium williamsoni* and the agglutinating *Jadammina macrescens* were present. All other species did not account for more than 3% of the total.

Ostracoda assemblage

Of the 46 valves and 4 species present *Leptocythere castanea* comprised over 78%. *Leptocythere lacertosa* (22%), *Elofsonia baltica* (<1%) and *Semicytherura nigrescens* (one valve) were all also recorded.

Diatom assemblage

The Marine Tychoplanktons *Raphoneis minutissima* (22%) and *Raphoneis surirella* (5%) make this group well represented. Marine/Brackish Epipelon species, however, dominate this assemblage with 42% of the total. *Navicula cincta* which dominated at Location 1 is not, however, recorded here. Instead the high numbers recorded for this lifeform group are made up of a diverse set of species which include *Navicula flanatica*, *Navicula halophila*, *Navicula pygmea*, *Nitzschia acuminata* and *Nitzschia punctata* spp.. Ecology Unknown remains at *circa* 12% and no other lifeform group exceeds 5%.

4.4.4 Sample 3

Environment: standing water in intertidal gully (end furthest from main channel)

Altitude: 3.37m O.D.

Grid reference: NX 46218 60320

Particle size percentage: Clay 0.7%; Silt 58.8%; Sand 40.5%

The gully selected for sampling runs approximately parrallel to the sampled traverse. Sediment slumping due to the gully erosion has allowed the formation of ponds in the bottom of the gully at points along its length. This sample was taken from a small pool situated at the furthest point from the main channel.

Foraminifera assemblage

There was a low number of individuals (40) in the sample which recorded 9 different species. Of these *J. macrescens* dominates with nearly 50% of the total. *Ammonia limnetes*, *E. williamsoni*, *Elphidium excavatum* forma *lidoensis* and *H. germanica* were all present but at values lower than 10%. Other species made up *circa* 15% of the assemblage.

Ostracoda assemblage

Only two valves of *L. castanea* were recorded and probably represent an allochthonous component having been washed in during a previous inundation by the tidal waters.

Diatom assemblage

The Marine Tychoplanktons fall markedly in representation to *circa* 6%. Marine/Brackish Epipelon species continue to dominate with *circa* 74% of the total. The main species in this highly diverse group are *Navicula cincta*, *Navicula flanatica*, *Navicula halophila* and *Navicula phyllepta*. Ecology Unknown is at *circa* 10% and no other lifeform group exceeds 5%.

4.4.5 Sample 4

Environment: high saltings terrace next to low saltings terrace
Altitude: 4.40m O.D.
Grid reference: NX 46302 60321
Particle size percentage: Clay 0.4%; Silt 67.4%; Sand 32.2%

The location of this sample was on the high saltings terrace (as for location 1) on top of the bluff that marked the change to the low saltings terrace. Both of these levels comprise the saltings.

Foraminifera assemblage

Similar to location 1 the sample here revealed low numbers of foraminifera (6 tests) and it is probable that these are allochthonous having been carried in during a previous inundation by the tidal waters.

Ostracoda assemblage

No ostracoda were recorded

Diatom assemblage

The Marine Tychoplanktons remain present but in low numbers at *circa* 8%. The Marine/Brackish Epipsammon group is recorded at 12% resulting from a peak in *Denticula subtilis*. Marine/Brackish Epipelon species continue to dominate at *circa* 80% of the total assemblage with the main species of *Navicula cincta, Nitzschia debilis* and *Nitzschia filiformis*. Ecology Unknown is relatively low at *circa* 6% and no other lifeform group exceeds 5%.

4.4.6 Sample 5

Environment: standing water in intertidal gully (end closest to main channel)
Altitude: 3.04m O.D.
Grid reference: NX 46317 60309
Particle size percentage: Clay 0.7%; Silt 72.4%; Sand 26.9%

As for location 3 a sample was taken from a pool in the bottom of a tidal gully. This location is positioned much closer to the estuary channel.

Foraminifera assemblage

A similar number of tests (46) were recorded from this location compared to location 3. All the main species recorded at location 3 are present, however, the dominant species has changed from *J. macrescens* to *H. germanica* which accounts for 43% of the population. Species diversity has increased to 16 species and this is reflected in the percentage of other species present which comprise approximately 35% of the total. It was noted that these were predominantly small tests of marine (inner shelf) species that probably represent an allochthonous, size sorted component of the assemblage brought in during high tides.

Ostracoda assemblage

Of the 21 valves and 8 species recorded *L. castanea* comprised 57% of the total. *Palmoconcha laevata* accounted for 19% of the valves recorded (equal to 4 valves) with the 2 of *L. lacertosa* approximating to 9%. All other species were represented by one valve.

Diatom assemblage

The Marine Tychoplanktons *Raphoneis minutissima* (14%) and *Raphoneis surirella* (4%) make this group well represented. Marine/Brackish Epipelon species, however, dominate this assemblage with *circa* 45% of the total. The high numbers recorded for this lifeform group are made up of a diverse set of species which include *Navicula cincta*, *Navicula flanatica*, *Navicula halophila* and *Navicula phyllepta*. Freshwater Epiphytes increase to *circa* 6%. Ecology Unknown is at *circa* 20% and no other lifeform group exceeds 5%.

4.4.7 Sample 6

Environment: intertidal low vegetated saltings

Altitude: 4.33m O.D.

Grid reference: NX 46320 60320

Particle size percentage: Clay 0.4%; Silt 56.8%; Sand 42.8%

The low vegetated saltings is easily distinguished from the high saltings level due to the marked bluff between the two and the change in colour and density of the grass dominated vegetation which visibly lightens and thins. One sample was taken from this 15 metre wide terrace that ends on an eroding marsh cliff-face that drops down to channel intertidal mudflats.

Foraminifera assemblage

Jadammina macrescens dominates this assemblage at 63% of the 113 tests recorded. *Haynesina germanica*, *A. limnetes* and *E. williamsoni* are all also recorded in numbers. Other species make up approximately 10% of the total population and probably represent an allochthonous component.

Ostracoda assemblage

Three valves were recorded from this location and there were an equal number of species. These undoubtedly represent an allochthonous assemblage.

Diatom assemblage

There is a slight fall in the numbers of the Marine Tychoplanktons *Raphoneis minutissima* (8%) and *Raphoneis surirella* (5%) from the previous location. Marine/Brackish Epipelon species continue to dominate the diatom assemblage with *circa* 67% of the total. The main species in this group are *Navicula cincta* (38%), *Navicula halophila*, *Navicula phyllepta* and *Navicula pygmea*. Ecology Unknown is at *circa* 15% and no other lifeform group exceeds 5%.

4.4.8 Sample 7

Environment: unvegetated brackish pool on low saltings terrace (some seaweed present)

Altitude: 4.15m O.D.

Grid reference: NX 46316 60340

Particle size percentage: Clay 0.3%; Silt 52.2%; Sand 47.5%

On the low saltings surface exist large shallow brackish ponds which are unvegetated but support a sparse seaweed population. Sediment from the centre of one of these ponds was taken.

Foraminifera assemblage

Population numbers were high easily exceeding 300 individuals. *Haynesina germanica* dominates the assemblage realising *circa* 70% of the total. *Ammonia limnetes*, *E. williamsoni* and *E. lidoensis* are all present but never individually exceed 5% of the population. Of particular note is the near absence of *J. macrescens* which dominated on the vegetated part of the low saltmarsh. Diversity is high but the presence of other species does not exceed 10% of the population.

Ostracoda assemblage

Total number of valves recorded were 28 representing 9 species. *Leptocythere castanea* is the dominant species with over 60% of the population.

Diatom assemblage

The Marine Tychoplanktons *Raphoneis minutissima* (15%) and *Raphoneis surirella* (5%) make this group well represented. Marine/Brackish Epipelon species, however, once again dominate this assemblage with 46% of the total. The main species in this group are *Gyrosigma spencerii*, *Navicula cincta*, *Navicula halophila*, *Navicula phyllepta* and *Navicula pygmea*. Ecology Unknown remains at *circa* 16% and no other lifeform group exceeds 5%.

4.4.9 Sample 8

Environment: high intertidal channel mudflat

Altitude: 2.69m O.D.

Grid reference: NX 46347 60322

Particle size percentage: Clay 0.2%; Silt 38.6%; Sand 61.2%

The location of the next sample is on the steeply sloping unvegetated intertidal mudflats that flank the Cree river channel close to the cliff that marks the end of the low saltings terrace.

Foraminifera assemblage

Haynesina germanica remains the dominant species represented but with a sharp reduction in its share of the population with a percentage of 28%. *Elphidium williamsoni* (21%) and *A. limnetes* (9%) both are recorded in reasonable numbers. The main proportion of the assemblage is, however, taken up by a diverse marine (inner shelf) species population which account for *circa* 35% of the total. This high value probably represents the regular submergence by the tide which washes in the size sorted allochthonous forms from Wigtown Bay.

Ostracoda assemblage

Leptocythere castanea is the dominant species with 54% of the 74 individual valves recorded. Of the other 14 species the most notable are *Cytheropteron nodosum* (11%) and *Paradoxostoma normani* (7%). None of the other species exceed 4% (equal to 3 valves).

Diatom assemblage

Numbers of Marine Tychoplanktons increase with *Raphoneis minutissima* (18%) and *Raphoneis surirella* (5%) supported by low numbers of *Cymatosira belgica* (2%) and *Plagiogramma vanheurckii* (3%). Marine/Brackish Epipelon values fall to *circa* 33% with the main species of *Navicula cincta* and *Navicula flanatica*. Ecology Unknown numbers increase to *circa* 28% and no other lifeform group exceeds 5%.

4.4.10 Sample 9

Environment: low intertidal channel mudflat

Altitude: 1.42m O.D.

Grid reference: NX 46372 60324

Particle size percentage: Clay 0%; Silt 16.6%; Sand 83.4%

This location is similar to the previous one but is positioned much closer to the Cree channel. The particle size distribution clearly shows the coarseness of the sediments close to the channel.

Foraminifera assemblage

The similarity between this assemblage and that from location 8 is striking. Only the slight increase in the number of *A. limnetes* to *circa* 24% is the most notable change.

Ostracoda assemblage

Of the 64 valves and 18 species recorded *L. castanea* remained as the main species with 22% of the population. Three other species were, however, also recorded in numbers. These were *L. lacertosa* (12.5%), *P. laevata* (17%) and *C. nodosum* (12.5%) all of which are commonly found in estuaries. The high diversity of other species in low numbers probably represent the allochthonous component of the assemblage.

Diatom assemblage

Although numbers of Marine Tychoplanktons fall slightly to 20% this is dominant and continues to be comprised mainly of *Raphoneis minutissima* (13%) and *Raphoneis surirella* (7%). Marine/Brackish Epipelon values fall to *circa* 16% with no one species prominent. Freshwater Epiphytes increase to *circa* 6% of the total assemblage. Ecology Unknown is the dominant group with a further increase to *circa* 39%. No other lifeform group exceeds 5%.

4.4.11 Sample 10

Environment: intertidal mudflat close to marine waters of Wigtown Bay
Altitude: 2.63m O.D.
Grid reference: NX 244635 556350
Particle size percentage: Clay 0.7%; Silt 78.4; Sand 20.9%

Location 10 was on the gently sloping and extensive unvegetated intertidal mudflats that are close to the open marine waters of Wigtown Bay. The course of the main Cree channel was *circa* 2km from the location at its nearest point.

Foraminifera assemblage

The numbers of tests at this location easily exceeded 300 individuals of which *circa* 70% are *H. germanica*. *Elphidium williamsoni* was well represented with 21% of the total. Although 18 other species were identified together they did not exceed 10% of the assemblage.

Ostracoda assemblage

Valve abundance was high with the count easily exceeding the 300 required. Species diversity was however low with only five species recorded. Of these *L. castanea* dominated with 90% of all valves recorded. *Leptocythere lacertosa* realised 9% of the total with the other three species represented by one valve of each.

Diatom assemblage

The Marine Tychoplanktons dominate this assemblage with high numbers of *Raphoneis minutissima* (19%) and *Raphoneis surirella* (6%). Marine/Brackish Epipelon species are well represented (20%) although of the 15 species present only *Amphora acutiuscula* exceeds 5% of the total. The dominant group is that of Ecology Unknown at 38%. No other lifeform group exceeds 5%.

4.4.12 Location 11

Environment: intertidal sandy beach at Brighouse Bay

Altitude: 1.49m O.D.

Grid reference: NX 4533 6341

Particle size percentage: Coarse sand (not processed)

The intertidal sands of Brighouse Bay were sampled from a location that has a diurnal tide throughout the year (i.e. below MHWNT). The bay is flanked by a rocky shoreline which provides suitable conditions for rock pools. There is no significant freshwater input to the bay.

Foraminifera assemblage

A high number of individuals (278) were counted from this location of which *circa* 78% are *Ammonia batavus*. *Elphidium lidoensis* made up 12% of the assemblage. Eight other species made up the remainder with *Elphidium macellum* making a notable appearance. *Haynesina germanica* recorded only a presence.

Ostracoda assemblage

The 53 valves (5 carapaced) recorded were made up of a very diverse assemblage comprised of 15 separate species. No one species, however, exceeds 6% of the total. *Cythere lutea* (5%), *Loxoconcha rhomboidea* (5%), *Bonnyanella robertsoni* (4%) and *Hemicythere villosa* (3%) were the main species present. The occasional colder water species, including *Robertsonites tuberculatus* and *Hemicytherura clathrata*, record a presence. It is possible that these have been reworked from sediments deposited during the last glaciation.

Diatom assemblage

No sample was analysed from this location.

4.5 The microfaunal biozones for the Cree estuary region

Distinct changes in the composition of the diatom assemblages between each location could not be unequivocally identified. There is some indication that Marine/Brackish epipelon species tend to dominate the saltings surfaces with Marine Tychoplanktons increasing on the intertidal mudflats. However, the high diversity of each assemblage and the often sporadic nature of particular species' abundance makes it impossible to assign a diatom assemblage to a specific biozone. Furthermore, the known ecological requirements of the Marine Tychoplanktons (Underwood, 1994) indicates that all species in this well represented group are probably allochthonous to each assemblage. The following biozones are therefore based on the foraminifera and ostracod data.

Biozone for high saltings terrace

Barren of foraminifera and ostracoda apart from the occasional transported test or valve.

Biozone for intertidal gullies

Low abundance of species. Variable population structure ranging from one similar to the low saltmarsh biozone (where *J. macrescens* dominates and no ostracods) to one similar to the brackish pools on the saltings surfaces (where *H. germanica* and *L. castanea* dominates). *Ammonia limnetes* and *E. williamsoni* are recorded in low numbers (<10%) at both sites. It is highly probable that the marsh species were incorporated into the assemblages as a result of sediment slumping and were not *in situ*. Diversity may increase closer to the channel where transported tests are more readily deposited.

Biozone for low intertidal vegetated saltings terrace

The agglutinating foraminifera *J. macrescens* is the dominant species exceeding 60% of the total population. Other brackish/euryhaline foraminifera species are also present. No ostracoda apart from the occasional allochthonous valve were recorded.

Biozone for intertidal brackish pools

Foraminifera abundance is high with the euryhaline *H. germanica* dominating the assemblage with 60 - 80% of the total population. *Leptocythere castanea* similarly dominates the ostracod fauna but abundance of valves is poor. Allochthonous component appears to increase with increased regularity of tidal inundation.

Biozone for intertidal mudflats close to the river channel

Species abundance is relatively high as is species diversity with large numbers of size sorted marine (inner shelf) species present. No one foraminifera species clearly dominates with *H. germanica*, *A. limnetes* and *E. williamsoni* recording between 10% and 30% of the total count. Ostracoda diversity increases closer to the river channel with *L. castanea* remains the most common (but not dominant) species.

Biozone for intertidal mudflats close to open marine conditions

Species abundance is high with both *H. germanica* and *L. castanea* dominating each faunal group with between 60% and 90% of the total population. Only the brackish species of *E. williamsoni* and *L. lacertosa* are recorded in any numbers (between 10% and 20%). Of the foraminifera allochthonous marine (inner shelf) species comprise *circa* 10% of the assemblage. Ostracod diversity is very small indicating few allochthonous valves.

Biozone for intertidal sands

Species abundance is high with *A. batavus* dominating the assemblage with up to 80% of the total population. The more marine *Elphidium* spp. are also commonly present. Species diversity is relatively low. In contrast ostracod diversity is relatively high with species abundance low. Ostracod species that are common to open marine waters and higher salinities dominate the assemblage and, as such, possibly represent an allochthonous component with few carapaced forms present.

4.7 Summary

The results of this surface survey of the microbiota of the intertidal environments of the Cree estuary region have produced new evidence for distinctive biozones in relation to a tidal level. The most distinctive of these being the *J. macrescens* dominated low saltings biozone. As a result of the levelling of the high and low saltings terraces (Section 4.3) it has been shown that these two distinct facies do not have a dissimilar altitude range (i.e. between 4.05-4.50m O.D.). This altitude range of the saltings terrace means that it is inundated only on the highest of tides between present MHWST (3.8m O.D.) and HAT (4.9m O.D.) as recorded at Kirkcudbright Bay tide gauge. Therefore the *J. macrescens* dominated biozone will be taken to approximate to a former M^1 level when present in the fossil record. At the present time M^1 has been calculated as 4.35m O.D. for the Kirkcudbright Bay tide gauge.

Although the above biozones provide a framework for palaeoenvironmental interpretations in this research it is deemed advisable to use these results in combination with the results from similar studies elsewhere in the British Isles. One of the obvious deficiencies of this survey is that samples were not taken throughout the year in order to identify seasonality in foraminifera, ostracod and diatom populations. Further, the relationship between living and dead populations may reveal a more accurate picture of species distribution in estuarine environments.

Undoubtedly, one primary objective of future research must be that a comprehensive survey of the foraminifera, ostracoda and diatoms in the estuaries around the coastline of Scotland is undertaken - a region that has been neglected for such studies. Nonetheless, the results presented above give an indication of the variability in the microbiota populations in different intertidal environments and broadly correspond with the evidence from similar studies elsewhere in the British Isles (e.g. Haynes, 1973; Coles, 1977; Coles and Funnell, 1981; Murray, 1971; 1979; 1991; Penney, 1987; Athersuch *et al.*, 1989).

Chapter 5 Brighouse Bay

5.1 Introduction and background information

5.1.1 Site and situation

Brighouse Bay (NX 630 450) is a narrow inlet at the south eastern extremity of the Wigtown Bay coastline close (*circa* 2 km) to its intersection with the smaller Kirkcudbright Bay and lying approximately 25 km south east of the Wigtown Bay carseland areas (Figure 5.1). The bay is the outlet of a valley *circa* 2 km in length and *circa* 400 m broad draining SSW with both valley sides rising to a maximum height of *circa* 50 m O.D.. Geologically, the rock exposures that flank the bay are of well-bedded, repeatedly folded and sheared greywackes of the Carghidown Formation (Hawick Group, Llandovery Series, Silurian) (Stone, 1996). The 500m of gently sloping sandy intertidal zone leads up to a sand and shingle beach behind which lies a stabilised dune system which is intersected by a small stream. To the immediate north of the dune system is a small (*circa* 100 m^2) area of freshwater marshland which is the focus of the present study.

5.1.2 The gas pipeline landfall site

A project to connect the Irish and U.K. gas transmmission pipeline networks by Bord Gais Eireann commenced in 1992 and following identification of a series of prospective landfall sites - where the pipeline enters the sea - Brighouse Bay was identified as the most suitable location in both environmental and engineering terms (R.S.K. Environment Ltd., 1992). Due to the nature and size of such a project, Brighouse Bay (as an SSSI) was the focus of both a preliminary Environmental Statement prepared by R.S.K. Environment Ltd. (prior to engineering work) and further environmental investigations during construction (see Maynard, 1994a). The author's research did not coincide with the pipeline excavation of the dune system and adjacent intertidal zone which had taken place some months earlier. However, spoils from the pipeline trenching through the foreshore were still abundant within the intertidal zone. A distinctive red/pink silty clay with some small stones was present but no accurate stratigraphical control could be placed on these sediments. There is some indication that these sediments can be found in patches around Brighouse Bay (Sproat, *pers. comm.*) but none was positively identified in the present study. A sample of these sediments has been taken and prepared for foraminifera and ostracoda analysis (see section 5.4.7).

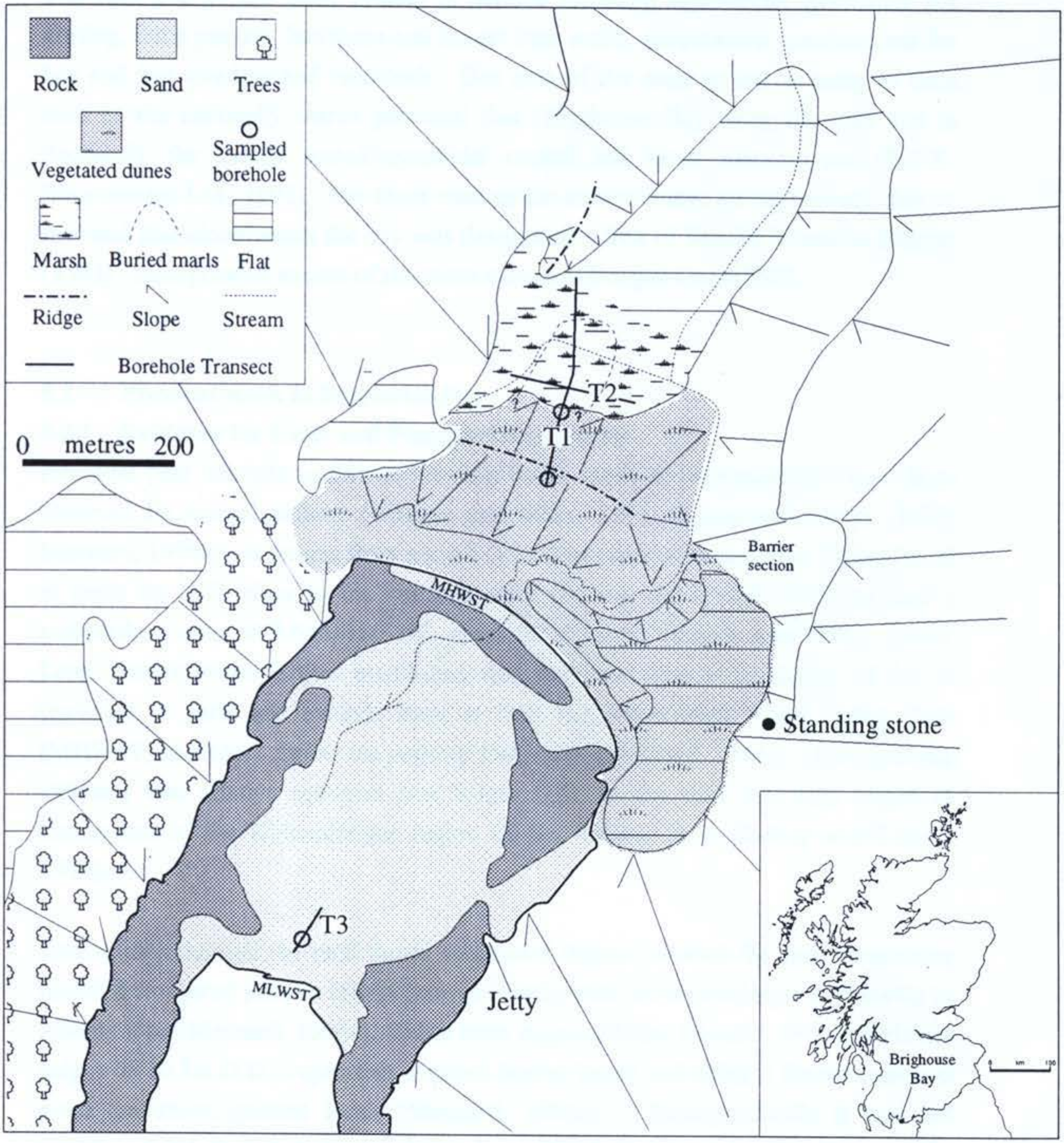


Figure 5.1 Brighouse Bay: geomorphological map showing borehole transects

5.1.3 The dune system: current land use

The land use of the dune system is diverse including agricultural grasslands for grazing, dune pasture, hawthorn and burnet rose scrub, semi-natural grassland cut for hay and wet meadow and reed beds. One area of the dune system is home to flora such as the nationally scarce perennial flax (Brighouse Bay being the only site in Scotland), the locally scarce pyramidal orchid and lesser meadow rue (R.S.K. Environment Ltd., 1992). For these reasons the area of dunes on the seaward side of the road that circumvents the bay was designated a Site of Special Scientific Interest (SSSI) - incorporated as part of the more extensive Borgue Coast SSSI.

5.2 Previous work at Brighouse Bay

5.2.1 Evidence for Late- and Post-glacial sea-levels

Intertidal peat deposits underlying modern beach sands at Brighouse Bay have been observed by several authors (Godwin and Willis, 1961; Bishop and Coope, 1977; Maynard, 1994a). A sample from a small (15 x 15m) area of woody peat (30cm thick) at *circa* 0m O.D. close to the low tide mark (Bishop and Coope, 1977) realised a radiocarbon date of 9,640±180 ^{14}C years BP (Q-398; Godwin and Willis, 1961). Later investigations further established that the peat layer is in excess of 2m in thickness in parts and extends from at least the Mean High Water Spring Tide (MHWST) mark to '*...below the point of low water*' (Maynard, 1994a). This evidence indicates that relative sea-level was below O.D. at the time that peat began to accumulate in the Kirkcudbright region of the Solway Firth (Bishop and Coope, 1977).

Excavations through the sand dunes revealed a deposit beneath the sand comprising rounded elongated pebbles (50-200mm in length) with occasional larger cobbles up to 300mm long (Maynard, 1994a). It has been suggested that this unit, with a maximum height of 10.3m O.D., represents a raised barrier beach indicating a former sea-level *circa* 8m above present levels (Maynard, 1994a). Stratigraphically it was not established whether this deposit was above the buried peat layer underlying the modern beach. However, its formation is thought to have occurred at - or shortly after - the maximum of the Flandrian transgression sometime after 7,500 ^{14}C years BP and before the late Bronze Age when sand dune formation was initiated (Maynard, 1994a). Rapson (in Maynard, 1994a) proposed on the basis of stratigraphical and palynological studies of the marsh area behind the dune (within the present study area) that the lowest deposit of "blue/pink clay" at approximately 6.5m O.D. is that of the "Main Postglacial carse clays". Her interpretation was not, however, supported by either a detailed stratigraphic survey of the area nor microfossil analysis. In addition no organic material from the sampled core was radiometrically dated to provide corroborative evidence.

5.2.2 Archaeological evidence at Brighouse Bay

Approximately 100m east of the northern most shore of the bay is a single standing stone; the archaeological context of this stone is not known. As a result of the pipeline trenching through the dune system, Maynard (1994a) identified three sand (aeolian) units separated by two buried organic rich/soil layers all of which stratigraphically overlie the 'raised storm beach' deposit (see Figure 5.2). Associated with the uppermost soil layer are a number of shell middens. The timing of the development of these layers is uncertain although the lowermost soil layer is attributed to the late pre-Roman period with the latter layer being of Roman age (Maynard, *op cit.*). It is possible to suggest a late Bronze Age date for the lowest dune sand deposit. The dating of the upper buried soil layer was assisted by the limited but informative artefacts found in stratigraphical association with it. These included a mould for false Roman denarii, a Fraser Hunter iron spearhead and additional metal pieces, ceramics and stone objects. The nature of these objects, the plough marks and the shell middens all indicate the likelihood of a settlement site at Brighouse Bay during at least some part of the Roman occupation of Britain. The uppermost sand deposit has been suggested as having developed during the eighth and ninth centuries AD. Buried burnt mounds running close to or cut into by the present stream were discovered and excavated, but no radiocarbon dates were obtained (Maynard, 1994b).

5.2.3 Palaeoenvironmental reconstruction at Brighouse Bay

Bishop and Coope (1977) undertook palynological and coleopteran analysis on the foreshore buried peat deposit. The interpretation of their results indicates that the peaty deposit accumulated in a marsh, richly overgrown with *Typha* and *Phragmites* and probably also by *Carex* and *Sparganium* and would probably have been surrounded by deciduous woodland. The implications of the coleopteran assemblage suggests that the climatic recovery after the Loch Lomond Stadial must have been exceedingly rapid so that by the time the Brighouse Bay peat deposits were formed the climate was at least as warm, or even slightly warmer, as in SW Scotland today.

Rapson (in Maynard, 1994a) undertook a palynological investigation on three cores from the farmland to the north of the dune as part of the environmental appraisal associated with the gas pipeline construction. Six local pollen chronozones were identified of which the lowest (BB1) was correlated with the upper levels of the suggested Main Postglacial Shoreline. Peat formation was thought to have been initiated by approximately 7,000 ^{14}C years BP after relative sea-levels fell following the maximum of the Main Postglacial Transgression. The pollen evidence that peat initiation occurred in a salt marsh environment appears to be at best equivocal. The interpretation from the pollen assemblage that the Brighouse Bay area was covered by a mixed deciduous forest (predominantley hazel, oak and alder) prior to human impact is more certain. An initial elm decline at approximately 5,000 ^{14}C years BP is indicated although lasting forest decline is thought to have taken place sometime after this period and has been associated with prehistoric human occupation at Brighouse Bay. Exact locations of each borehole investigated by Rapson were not given and an O.D. height for the main borehole was not provided.

5.3 Stratigraphical survey

5.3.1 Introduction

The field system to the north of the dunes at Brighouse Bay was the focus of this investigation after a series of preliminary boreholes were undertaken. Due to the small size of the area and detailed stratigraphy, boreholes were sunk at close intervals on a 25m grid system. In total 80 boreholes were made ranging in depth from *circa* 40 - 700cm and all were levelled in with a closing error not greater than 0.05m (see Figure 5.1 for borehole transect positions presented here). Representative borehole transects from both down-valley and cross-valley are presented as cross-sections in Figures 5.3a and 5.3b. Two additional boreholes were put down with a Dutch Geological Survey team through the dune system to locate the raised storm beach deposits. A short series of boreholes were made through the foreshore to identify further the sediments that are associated with the intertidal buried peat (see section 5.4.1).

5.3.2 Dune system and marshland stratigraphy (see Figures 5.3a and b)

The base of most boreholes is marked by a blue/grey deposit of silts, sands and gravels. This deposit is then succeeded by a brown silty peat. Seaward, however, peat development is interrupted by olive green shelly marl layers (*circa* 4 - 7 m O.D.). In borehole D1, which penetrated upper dune sand layers, the marls are not only proven to be continuous underneath the sand but also to overlie a lower sand deposit.

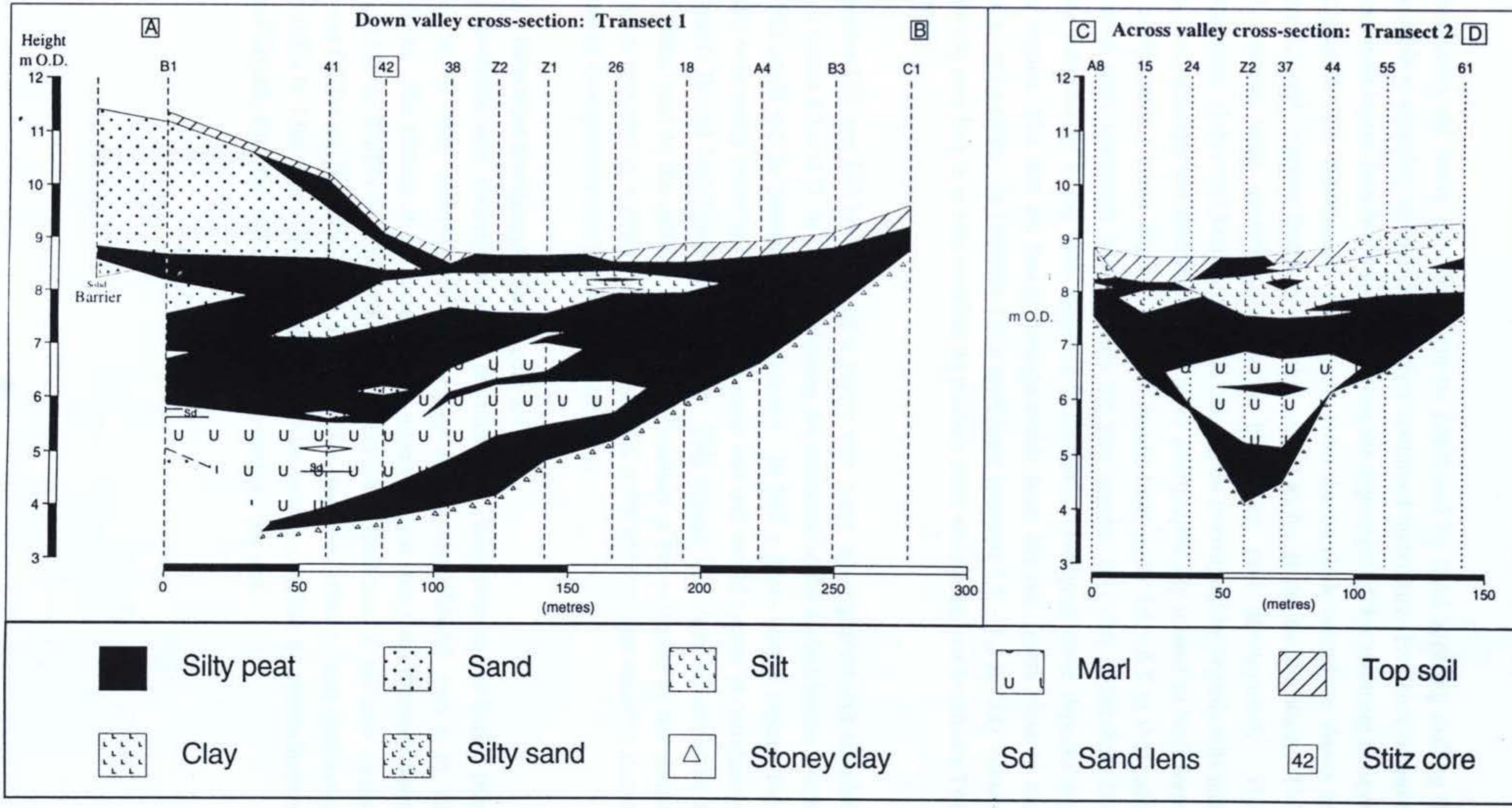


Figure 5.3 Lithostratigraphical cross-sections from the dune system and marshland - a) down-valley and b) cross valley

Unfortunately the lower sand could not be penetrated by hand augering making it impossible to establish whether a marl layer continued under this. Evidence of three distinct marl layers from borehole Z1 indicates the deposition of this sediment to have been phased. The distribution of the marls from the borehole records is shown in Figure 5.1 and indicates that they probably extend as far as the barrier beach. The marl deposits were eventually succeeded by further peat development. The development of this well humified peat is once again interrupted by organic silts and clays that, although not uniform, appear to be stratigraphically related in both form and composition. These deposits range in height from *circa* 7.5 - 8.5 m O.D. and appear to taper landwards (this excludes the grey organic silty clay in borehole D1 whose relationship to the other deposits is unclear). Overlying these deposits are more organic silts that are barely distinguishable from the soil layers close to the present land surface. In borehole D1 a sand layer between 7.5 - 8.2 m O.D. occurs within the peat that is in turn overlain by modern dune sediments (see boreholes T41 and T42).

Boreholes D/2 and D/3 both located a buried unit made up of gravels and rounded stones (*circa* 8.5m O.D. in D/3) confirming the existence of the buried barrier beach but this could not be penetrated once reached. In D/3 a 22cm buried organic rich deposit with sandy inclusions overlies the stone unit and would appear to correlate to Maynard's Buried Soil 2 (see section 5.2.2). This deposit is in turn succeeded by a sand (dune) unit to the surface. Further confirmation of the existence of the buried barrier is provided in a stream bank section (NX 6388 4576) where rounded stones are easily distinguished (see Figure 5.1 for location).

5.3.3 **Intertidal stratigraphy** (see Figure 5.4)

Four boreholes were undertaken across the foreshore. Sand overlies the buried peat which is, in turn, underlain by a blue/grey stoney clay/silt/sand matrix in all boreholes. The altitude of the surface of the minerogenic matrix rises landward from -0.5m O.D. in BB/F/4 to 1.34m O.D. in BB/F/1. The thickness of the peat ranges between 0.13m and 0.47m with the altitude of the peat/sand contact rising landwards from 0.3m to 1.6m O.D.. In borehole BB/F/3 the peat is overlain by approximately 5cm of organic silty clay with the beach sand overlying this unit.

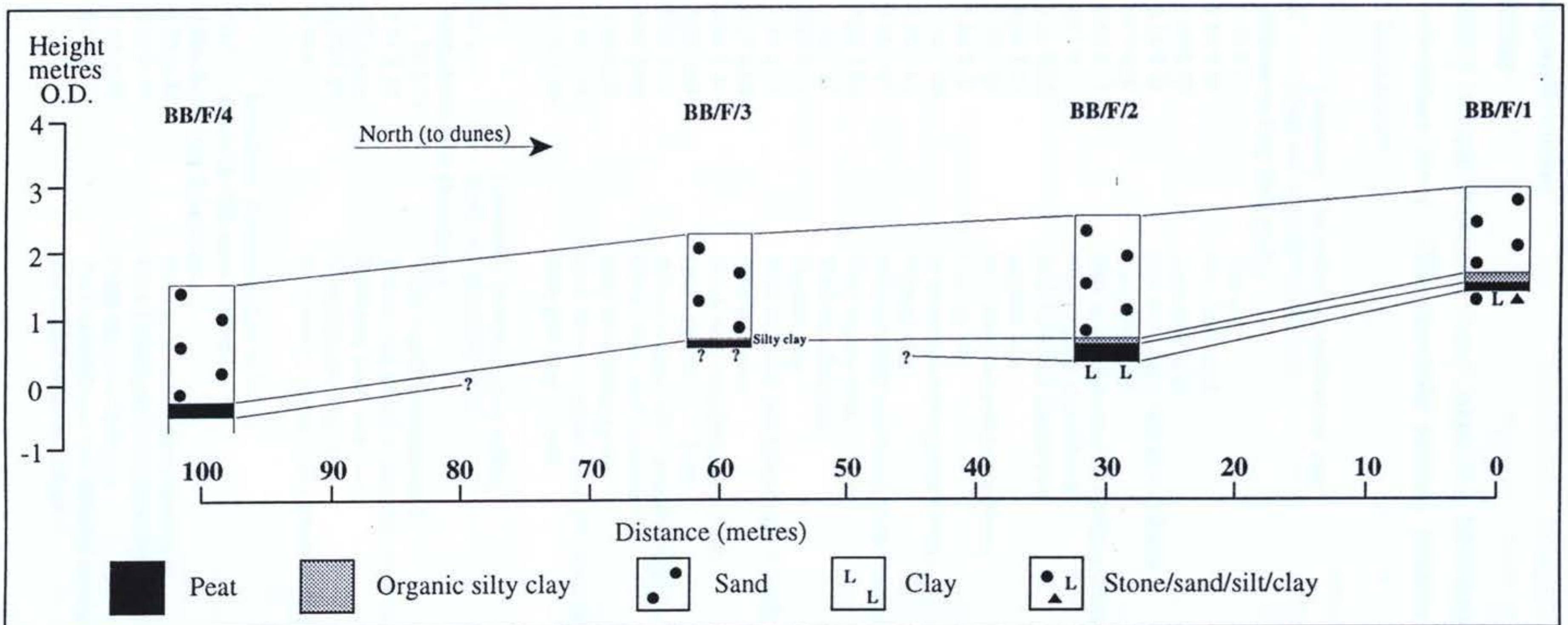


Figure 5.4 Brighouse Bay (foreshore transect): Lithostratigraphic cross-section

5.4 Biostratigraphic survey

5.4.1 Introduction

Three representative sample boreholes were taken for laboratory (microfossil) analysis and radiocarbon assay. The borehole number, location and borehole descriptions are listed below:

Borehole: T(4)2 **Location:** The marshland north of the dune
Height: 9.20m O.D. **Grid ref:** NX 263755 545982

Depth (cm)	**Altitude** (m OD)	**Description**
0-8	9.20-9.12	Top soil
8-40	9.12-8.80	Grey silty sand
40-42	8.80-8.78	Light grey sand
42-57	8.78-8.63	Peat with sandy inclusions (fibrous)
57-60	8.63-8.60	Dark grey sand
60-99	8.60-8.21	Dark brown fibrous peat + twigs + sandy inclusions
99-105	8.21-8.15	Very organic clay (fibrous)
105-116	8.15-8.04	Well humified fibrous peat
116-127	8.04-7.93	Organic clay
127-132	7.93-7.88	Well humified peat (some fibres)
132-141	7.88-7.79	Organic clay
141-151	7.79-7.69	Well humified peat (some fibres)
151-155	7.69-7.65	Organic clay
155-161	7.65-7.59	Well humified peat (some fibres + wood)
161-166	7.59-7.54	Very organic clay
166-183	7.54-7.37	Well humified peat
183-188	7.37-7.32	Organic clay
188-303	7.32-6.17	Well humified peat (Phragmites + sandy inclusions)
303-315	6.17-6.05	Dark blue sand
315-371	6.05-5.49	Black well humified peat + shells
371-412	5.49-5.08	Grey organic silt + shells
412-419	5.08-5.01	Brown organic silt to grey/green gyttja + shells
419-500	5.01-4.20	Olive green marl (laminated)
500-504	4.20-4.16	Dark olive green gyttja
504-547	4.16-3.73	Dark brown compact peat (gets more silty toward base)
547-564+	3.73-3.56+	Blue grey clay + clasts

Borehole: Dutch 3 **Location:** Middle of dune system
Height: 11.39 m O.D. **Grid ref:** NX 6375 4590

Depth (cm)	**Altitude** (m OD)	**Description**
0-265	11.39-8.74	Yellow medium/coarse sand
265-287	8.74-8.52	Brown well humified peat with sandy inclusions
287-313	8.52-8.26	Blue/grey sands and stones
313-325	8.26-8.14	Blue to brown/grey clay
325+	8.14+	Hit rounded stones (could penetrate no further)

Borehole: BB/F/3 **Location:** Foreshore close to LWM
Height: 2.25 m O.D. **Grid ref:** NX 63441 45376

Depth (cm)	**Altitude** (m OD)	**Description**
0-158	2.25-0.67	Dark grey coarse shelly beach sand
158-163	0.67-0.62	Dark brown/grey silty clay + shell fragments
163-167	0.62-0.58	Light brown (silty?) peat
167-214	0.58-0.11	Dark brown/black well humified compact peat with occasional wood and fibres

The blue/grey diamict recorded at T42 and F/3 were found to contain no foraminifera, ostracods nor molluscs. Diatom, foraminifera, ostracod and mollusc analyses were attempted across the upper clay and peat bands (116-188 cm depth) in borehole T42 all of which proved the sediment to be devoid of these fossils. Foraminifera, ostracod and mollusc analyses have effectively established the sedimentary environment - particularly palaeosalinity - in the marls. The organic-rich deposits at D2 were investigated for pollen content alone to aid correlation with borehole T42. The foreshore sampled core (F/3) was initially investigated for pollen and diatom content across the peat and overlying silty clay boundary. The sediment was barren of diatoms. One sample only was therefore prepared for foraminifera, ostracod and mollusc analysis to establish the provenance of the silty clays. The results of all palaeoenvironmental investigations are presented below. For discussion of zonation criteria of all fossil investigations see section 3.3.10.

An additional sample was prepared for microfaunal analyses of the red/pink silty clays (see section 5.1.2) recovered from the spoils of the pipeline trenching. Although not identified in the present survey these deposits are thought to underlie the blue/grey minerogenic sediments in the foreshore. The complete results of this analysis are presented seperately in section 5.4.7.

5.4.2 Radiocarbon dates

After microfossil analysis, sediment samples from T42 and F/3 were submitted for radiocarbon dating. Five radiocarbon dates have been obtained from core T42 and one from core F/3. The details of each date and its environmental significance are summarised in Table 5.1. To assist in estimating the approximate age of vegetation changes recorded at the T(4)2 borehole a Time/Depth curve based on these (uncalibrated) radiocarbon dates has been constructed (Figure 5.5).

5.4.3 Pollen and charcoal analysis

5.4.3.1 Borehole: T42

In total 105 levels were prepared for pollen and charcoal analysis at varying intervals (1-8 cm) throughout borehole T42. The pollen data have been divided up into seven Local Pollen Assemblage Zones (LPAZs) (see Figure 5.6): the characteristics of each are presented and described in Table 5.2. A critical analysis and interpretation of each zone is detailed in the following sections.

Site/ borehole	Laboratory code	C^{14} date (years BP)	Age cal. Years BP (2 sigma) (* denotes max/min values)	Altitude (metres OD)	Altitude error (metres)	National Grid Ref. (NX) (10 or 12 figs.)	Material	Environment	Tendency	C^{14} Procedure
BB/4/2	Beta-83741	2360±70	2,710-2,165*	8.33 to 8.30	Not applicable	263755 545982	Peat	Human Impact clear - high herbs/low trees and shrubs	None	Standard
BB/4/2	Beta-83742	4970±60	5,890-5,600*	7.34 to 7.32	Not applicable	263755 545982	Peat	Human impact initiation/slope wash layers	None	Standard
BB/4/2	Beta-83743	6040±70	7,025-6,735	6.28 to 6.30	Not applicable	263755 545982	Peat	Above sand/aeolian layer	Negative?	Standard
BB/4/2	Beta-83744	7490±60	8,000-7,780	4.73 to 4.69	Not applicable	263755 545982	Marine Shell	End of brackish water sediments (marl)	Negative?	AMS
BB/4/2	Beta-83745	7660±60	8,510-8,335	4.19 to 4.16	Not applicable	263755 545982	Peat	Alder rise; Start of brackish water sedimentation	Positive?	Standard
BB/F/3	Beta-100913	8890±80	10,005-9,660*	0.62 to 0.60	±0.47 + 0.35	63441 45376	Peat	Foreshore peat underlying estuarine sediments - transgressive contact	Positive	Standard

Table 5.1 Radiocarbon date details for boreholes T42 (i.e. BB/4/2) and BB/F/B3, Brighouse Bay. Note that the conventional radiocarbon age of Beta-83744 has not been adjusted to account for the "old carbon" stored in marine shells: the regional value has been calculated as being *circa* 425 years and should be subtracted from the conventional age (an adjusted calibrated age is also necessary).

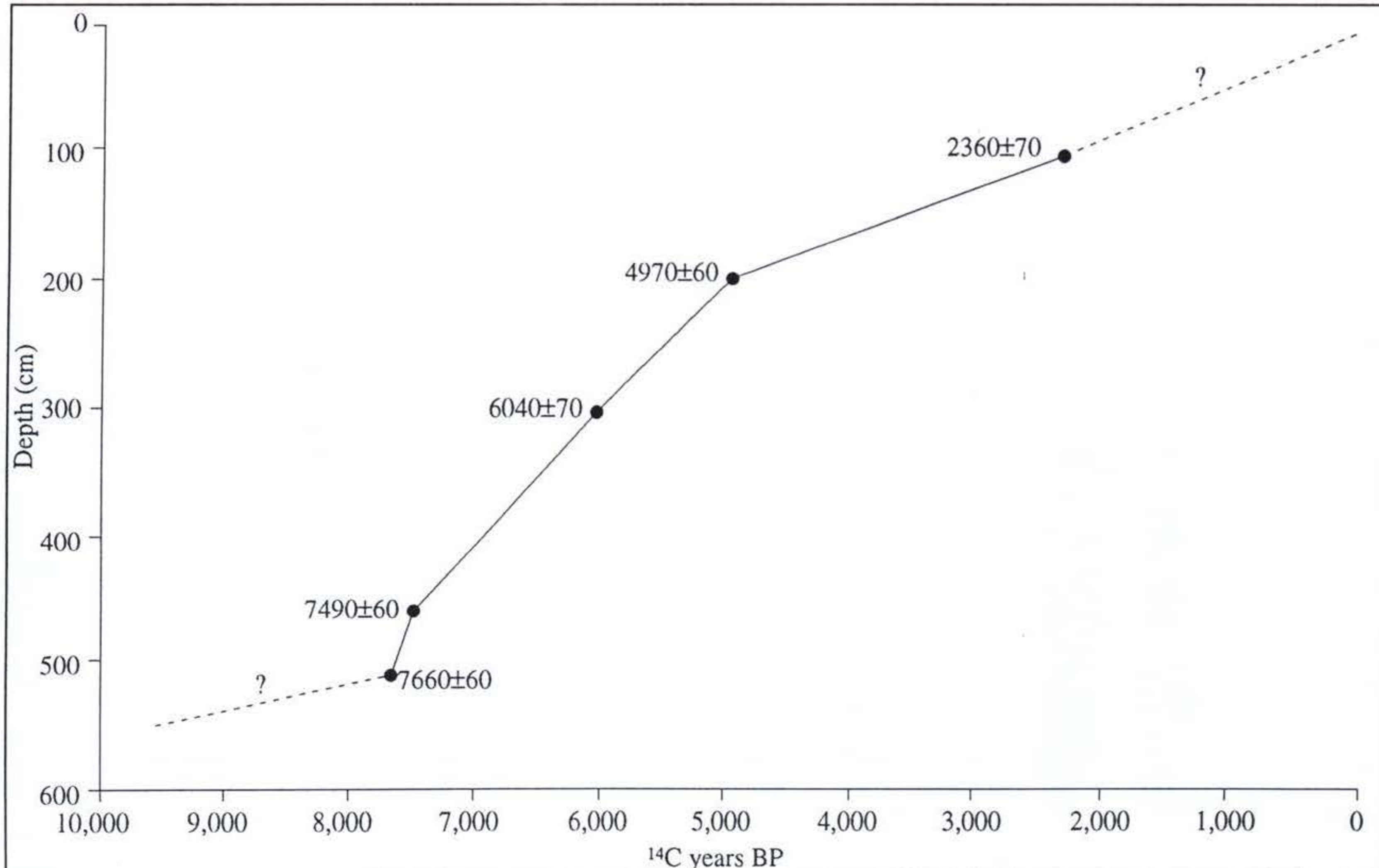


Figure 5.5 Time-depth graph based on the uncalibrated radiocarbon dates from borehole T42, Brighouse Bay

Figure 5.6 Brighouse Bay: Percentage pollen diagram + charcoal

Borehole: T(4)2
Height: 9.20m O.D.
Grid ref.: NX 263755 545982

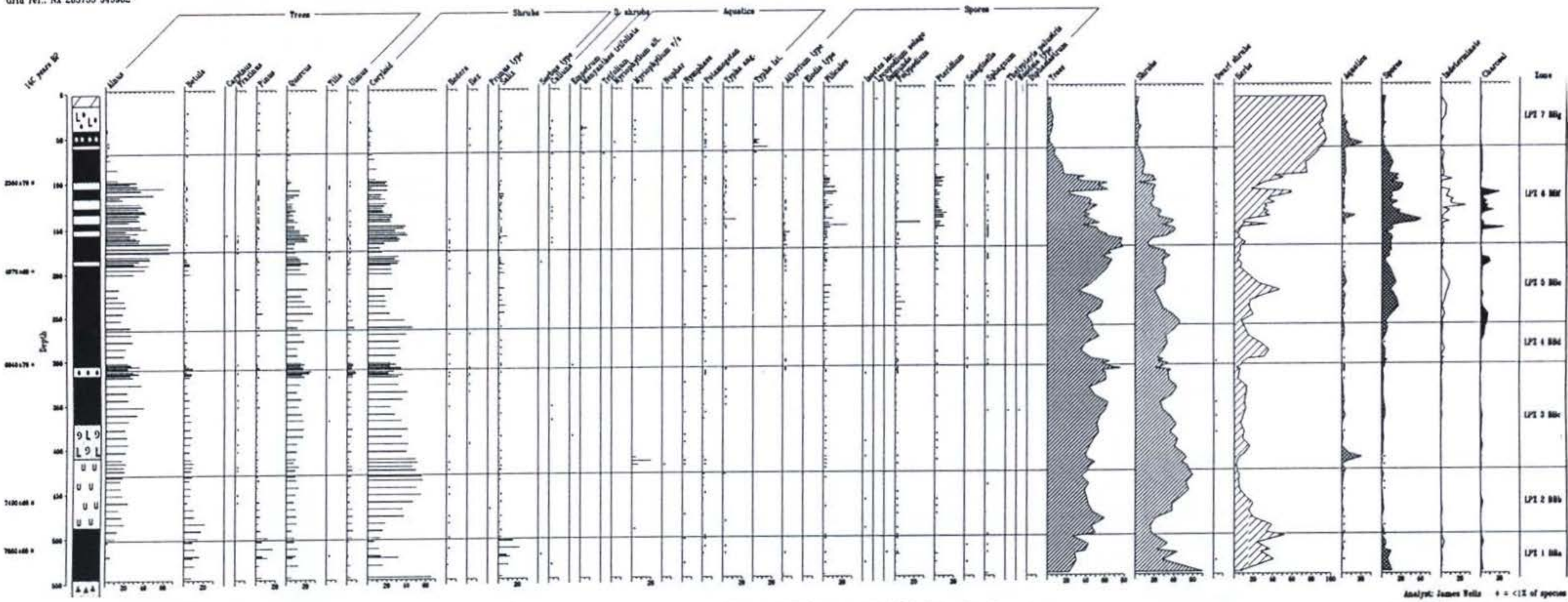
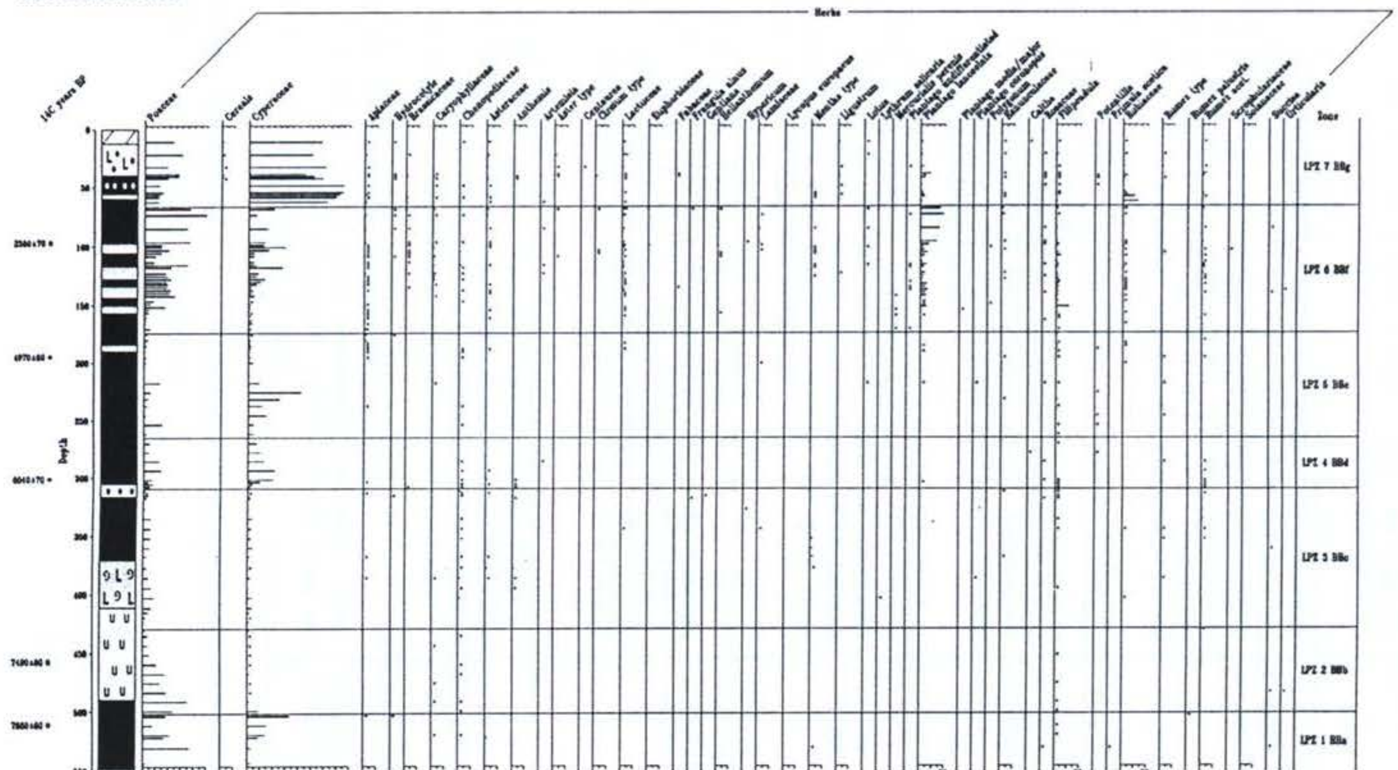


Figure 5.6 Brighouse Bay: Percentage pollen diagram + charcoal

Borehole: T(4)2
Height: 9.20m O.D.
Grid ref.: NX 263755 545982



Analyst: James Wells + = <1% of species

T42 LPAZ	Altitude (m O.D.) Depth (cm)	Main characteristics of the LPAZ	Duration (^{14}C BP)
BB/POL/7	**9.20-8.53** 0-67	**Cyperaceae - Poaceae** High values for Cyperaceae and Poaceae throughout the zone. Cereals record a noticeable presence from 50-0 cm. *Plantago lanceolata* present in low numbers throughout zone. AP values are low.	*c.*1,800 - present
BB/POL/6	**8.53-7.45** 67-175	***Alnus* - *Quercus* - Coryloid - Poaceae - Cyperaceae - *P. lanceolata*** *Alnus*, *Quercus* and Coryloid initially dominate although there is a general fall of AP values throughout the zone. Poaceae, Cyperaceae, *P. Lanceolata* and other herb values increase synchronously throughout to dominate by the upper limit of the zone. Filicales and *Pteridium* are well represented. Indeterminate grains and charcoal values fluctuate.	*c.* 4,500 - *c.*1,800
BB/POL/5	**7.45-6.55** 175-265	***Alnus* - *Quercus* - Coryloid** Stable values of AP throughout. Cyperaceae increases to a peak (*circa* 40%) mid-zone as do Indeterminable grains. Filicales and *Polypodium* values are a low but consistant component. Charcoal values record three noticeable peaks.	*c.* 5,700 - *c.* 4,500
BB/POL/4	**6.55-6.10** 265-310	**Coryloid - *Alnus* - *Quercus* - Cyperaceae - Poaceae** Stable values of AP throughout. *Ulmus* values are consistantly present in low numbers. Poaceae and Cyperaceae values increase synchronously to a peak mid-zone. Charcoal and spore values increase toward the upper limit of the zone.	*c.* 6,150 - *c.* 5,700
BB/POL/3	**6.10-4.90** 310-430	**Coryloid - *Alnus* - *Quercus* - *Betula* - *Ulmus*** Moderate fall in Coryloid values throughout zone whilst remaining dominant. Stable AP values for *Alnus*, *Betula*, *Quercus* and *Ulmus*. *Pinus*, Poaceae and Cyperaceae are all recorded at low but consistant values. *Myriophyllum verticillatum/spicatum* realise a small peak at 420cm.	*c.* 7,250 - *c.* 6,150
BB/POL/2	**4.90-4.18** 430-502	**Coryloid - *Alnus* - *Betula* - *Quercus* - Poaceae - *Ulmus* - *Pinus*** Strong increase in Coryloid percentages. *Alnus*, *Quercus*, and *Ulmus* values are stable throughout the zone. Decrease in *Betula* and *Pinus* values mid-zone. Poaceae values fall significantly to top of zone.	*c.* 7,630 - *c.* 7,250
BB/POL/1	**4.18-3.70** 502-550	**Coryloid - Poaceae - *Salix* - *Betula* - *Pinus* - *Quercus*** Significant fall in Coryloid values synchronous with falling Poaceae and increases in *Salix* and Cyperaceae. Values of *Betula*, *Pinus*, and *Quercus* are constant throughout the zone.	*c.* 7,630 - *c.* 9,600?

Table 5.2 Main characteristics and ages of Local Pollen Assemblage Zones (LPAZs) from borehole T42, Brighouse Bay.

BB/POL/1 (3.70-4.18m O.D.)

The blue/grey sediments at the base of the T42 borehole proved not to be polleniferous. The lowermost zone is therefore contained within the basal peat layer. The broad range of tree and shrub pollen provides evidence for a mixed woodland assemblage of *Quercus*, *Pinus*, *Betula*, *Corylus* and *Salix*. A poorly diverse meadow-type community is further indicated with high percentages of Poaceae and Cyperaceae pollen. Few other herbs record a significant presence. The presence of spores such as Filicales, *Polypodium* and *Pteridium* could indicate that these species were growing in the damp and cool conditions under the forest canopy.

In the upper limits of the zone *Pinus* and *Salix* pollen values peak but at no later part of the vegetational sequence do these taxa play such a significant role. It is suggested that this characteristic represents the drier conditions of the early Flandrian that allowed these species to flourish. The presence of *Alnus* pollen in this zone probably indicates the early stages of the much documented Alder rise (see Tallantire, 1992). The empirical limit of the *Alnus* rise is dated here at 7,660±60 ^{14}C years BP. Possible reasons for the spread and establishment of *Alnus* during the early Flandrian include increased climatic wetness, sea-level rise, Mesolithic activity, natural fires, beaver activity or the creation of suitable habitats through hydroseral successions and floodplain development (Huntley and Birks, 1983; Smith, 1984; Chambers and Price, 1985; Brown, 1988; Chambers and Elliott, 1989; Bennett and Birks, 1990; Edwards, 1990; Tallantire, 1993). The relationship at Brighouse Bay between the *Alnus* rise, the fall of *Pinus* and *Salix* pollen (see LPAZ BB/P/2 below) and the deposition of brackish sediments at about the same time (see later sections) makes it possible to infer that this phenomenon probably resulted from increased climatic wetness following the rising relative sea-levels of the Main Postglacial Transgression. At the nearby upland site of Round Loch of Glenhead in the Southern Uplands, a similar sequence is recorded with an *Alnus* pollen rise at 7,650 ^{14}C years BP followed by a short lived peak of *Pinus* pollen at 7,350 ^{14}C years BP (Jones & Stevenson, 1993). All these characteristics allow for a close correlation with this LPAZ and the Scottish Flandrian Zone III proposed by Moar (1969).

At nearby Loch Dungeon a pollen sequence records the expansion of *Ulmus* and *Quercus* by 8,500 ^{14}C years BP (Birks, 1972). More recently isochrone maps for these two species suggest that they expanded after 9,000 and 8,500 ^{14}C years BP respectively in SW Scotland (Birks, 1989). At Brighouse Bay in the lowermost levels indicate these two taxa to be already established. This might indicate that basal peat formation at this site did not commence at the beginning of the Flandrian but occurred sometime after. Previous investigations of the foreshore peat deposits at Brighouse Bay, however, record a similar mixed woodland pollen assemblage and a radiocarbon date of approximately 9,600 ^{14}C years BP (Bishop & Coope, 1977). If, as is suspected, the basal peat layer recorded in the stratigraphic sequence behind the dune system correlates with the foreshore peat then its development could well have been initiated close to 10,000 ^{14}C years BP. If this is the case then the Coryloid and *Betula* rises at this site appear to have occurred earlier than at other locations in the British Isles (see Birks, 1989). This is not implausible as Pennington (1977) has recorded a rapid transition from a Late Devensian vegetation to the *Betula* - *Corylus* zone of the early Flandrian on the Isle of Skye. Only absolute dating can confirm this suggestion.

High Coryloid pollen values in the lowest sample probably indicate that the early Flandrian *Corylus* rise predates this sequence although that this pollen could be *Myrica* is not dismissed (Edwards, 1981). This event has been recorded elsewhere in SW Scotland at around 9,200-9,300 ^{14}C years BP (Boyd & Dickson, 1986) although the evidence for this has since been questioned with the suggestion that this date refers to a second *Corylus* rise event (Birks, 1989). It has been indicated elsewhere that the combined birch and hazel expansions during the early Flandrian in this region probably occurred prior to 9,500 ^{14}C years BP (Birks, 1977; 1989).

BB/POL/2 (4.18-4.90m O.D.)
The second zone correlates with the marl deposit. The arboreal pollen assemblage is characterised by *Alnus*, *Betula*, *Quercus*, Coryloid and to a lesser extent *Pinus*, *Ulmus* and *Salix* which suggests a mixed woodland has been established close to the sample site. *Alnus* becomes well established, the percentages of *Pinus* pollen fall and *Salix* pollen values almost disappear. The reduction in the presence of the latter two species during the alder rise is a common phenomenon (see Bennett, 1984 and Brown, 1988 respectively) particularly on wetter soils (Birks, 1977) and has been related here to increased climatic wetness as a result of rising sea levels (see above). Moar's (1969) Scottish Flandrian Zone IV relates well to these features as it does for the following three LPAZs up to and including BB/POL/5.

Coryloid values increase considerably throughout the zone from 12% to 55% indicating that *Corylus* became the dominant arboreal species expanding rapidly on the fertile soils of this coastal area and in the absence of competition from taller, long-lived, dense-shade-producing trees (Birks, 1989). One possible result of the dominance of *Corylus* at Brighouse Bay is perhaps reflected in the Poaceae and other herb pollen curves which fall to *circa* 5% of the total assemblage. This change may indicate that the dense shade provided by a low *Corylus* scrub prevented the further development of the herb taxa.

This evidence indicates a wooded landscape dominated by hazel, alder and oak with some elm and pine surrounding a small lake/pond which is indicated by the marl sediments. It is possible that an alder carr existed at the margins of the water body.

BB/POL/3 (4.90-6.10m O.D.)

This zone is characterised by a period of stability in the pollen assemblage with *Alnus*, *Quercus*, Coryloid the main taxa present and to a lesser degree *Betula* and *Ulmus* all comprising approximately 85% of the total. This assemblage probably indicates the continued presence and consolidation of a mixed woodland in the Brighouse Bay area which was dominated by hazel, alder and oak. The occurrence of *Fraxinus* pollen throughout this zone is noticeable and suggests that this species grew locally between *circa* 7,000 and 6,000 ^{14}C years BP. Birks (1989) records that low numbers of *Fraxinus* grew in southern and central parts of England at this time in lightly shaded enclaves on seasonally wet basic soils within mixed-deciduous forests and in drier parts of fen-carr woods. Further he indicates that the spread of this species into SW Scotland occurred sometime after 5,000 ^{14}C years BP. This is clearly not the case at Brighouse Bay.

Herb pollen values remain low with some Poaceae, Cyperaceae and Chenopodiaceae recorded throughout the assemblage. In the lower half of the zone no distinctive hydroseral succession to mark the final stages of the marl deposits is recorded in the pollen and spore record. Only a peak in numbers of the aquatic *Myriophyllum verticillatum/spicatum*, two species that exist commonly around water bodies, indicates that such an event probably occurred. That this species was probably *M. spicatum* is suggested by its known tolerance of calcareous-rich water (Clapham *et al.*, 1987).

BB/POL/4 (6.10-6.55m O.D.)

No significant change in the composition of the arboreal taxa is recorded in this zone with the pollen assemblage still indicating a mixed deciduous woodland comprised of alder, hazel, oak, elm and birch. The most prominant feature of this zone is a distinctive increase in pollen values for Poaceae and Cyperaceae, both of which peak mid-zone. This increase follows almost immediately after a sand (aeolian?) layer was deposited during peat formation. It is hypothesised here that this event in some way provided the environmental conditions suitable for grass and sedge growth probably in the centre of the valley rather than the valley sides.

Herb diversity is otherwise poor in this zone. Spore values increase slightly with Filicales and *Polypodium* both being recorded in consistant but low values. As for the increase in grasses and sedges the rise in value of these spores may indicate that there was an opening up of the woodland canopy possibly as a result of the sand deposition episode. Alternatively the increases in indeterminable grains and charred particle concentrations may be recording early anthropogenic impacts on the local environment at Brighouse Bay. If these results do represent a human impact signature they are certainly within the timescale recorded for similar records elsewhere in Scotland (Tipping, 1996).

BB/POL/5 (6.55-7.45m O.D.)
This zone is characterised by high *Quercus, Corylus* and *Alnus* pollen which continue to be well represented throughout. *Betula, Pinus* and *Ulmus* all show declining pollen frequencies throughout the zone. This assemblage probably indicates that the mixed deciduous was still present at Brighouse Bay but that its composition was slightly altering. Certainly the increase in numbers of *Alnus* pollen in the uppermost levels suggests that this taxon was becoming the dominant woodland species. Further, the increased values for *Salix* pollen is noticeable implying that this shrub was playing a more significant role in the woodland at Brighouse Bay.

Of all the arboreal species that go in to decline throughout this zone it is perhaps the distinctive fall in numbers of *Ulmus* pollen in the uppermost levels that require further attention. Birks (1989) notes that there was a marked decline in *Ulmus* in the pollen records of the British Isles between *circa* 5,500 and 5,000 ^{14}C years BP. Traditionally the Mesolithic/Neolithic transition has been defined by the beginning of agricultural acitivity and in Britain this has generally been correlated with the *Ulmus* decline at about this time (Birks, 1977; Moe and Rackham, 1992; Mighall and Chambers, 1995). The reasons for this relationship have been much discussed although it is probable that both selective pollarding of this species for livestock fodder (Troels-Smith, 1960; Garbett, 1981) and a wave of Dutch elm disease (e.g. Perry and Moore, 1987) conspired towards its devastation in the mid-Flandrian (e.g. Peglar and Birks, 1993). With a radiocarbon date of 4,970±60 ^{14}C years BP approximately dating this subtle event at Brighouse Bay it is possible to suggest that it was a nearby human impact on the vegetation that resulted in the 'elm decline' at Brighouse Bay. The absence of large grass (cereal) pollen in this zone certainly indicates that farming, if human impact is assumed responsible for the elm decline here, was probably pastoral although an arable subsistence cannot be ruled out.

The Poaceae and Cyperaceae pollen frequencies both rise in the lower half of the zone but at 210 cm the numbers fall sharply again (<3% TLP). The reasons for this marked change are unclear from this evidence. A number of other herb species are also present including Apiaceae, Chenopodiaceae, Asteraceae, Liguliflorae, *Filipendula*, Rubiaceae and the first scatter of *Plantago lanceolata* pollen - a species commonly linked to anthropogenic induced vegetation disturbance. Increased numbers of spores and aquatics including *Potamogeton*, *Athyrium* type, Filicales and *Polypodium* all suggest an increase in local soil moisture. It is possible to conclude from this combined evidence that close to the site the woodland canopy was beginning to open up allowing the smaller plants to establish themselves. Peaks in indeterminate grains and charred particle values further distinguish this zone and provide possible evidence that anthropogenic activity at Brighouse Bay, rather than any natural phenomena, were responsible for these small changes in the pollen record.

BB/POL/6 (7.45-8.53m O.D.)
Stratigraphically this zone includes the intercalated peat and silty clay layers and is distinguished by falling tree and shrub pollen values, rising herb and spore percentages and significant peaks in charred particles and indeterminable grains. *Alnus*, *Quercus* and Coryloid pollen values show a gradual and staggered fall toward the upper levels of the zone by which point each taxon is at approximately 5% of TLP. *Betula*, *Pinus*, *Ulmus* and *Salix* pollen frequencies have all declined to <1% TLP at least by mid-zone. Clearly non-selective deforestation is taking place at Brighouse Bay although for the duration of this zone a local woodland remains broadly in place. One interesting addition to the pollen assemblage of this zone is the frequent record of *Calluna* although whether this represents a local or regional increase in this species cannot be determined.

The increase of herb taxa throughout the zone including particularly Poaceae (1-45% TLP) and Cyperaceae (0-25% TLP) further indicate that the local vegetation was shifting toward a more open landscape. The increased diversity of herb species further adds to the overall rise in total herb pollen numbers with many taxa recording a presence (e.g. Apiaceae, Liguliflorae, *Filipendula*, Rubiaceae, *Rumex acetosa/acetosella*). *Plantago lanceolata* is the most well represented of the herbs outside of Poaceae and Cyperaceae with a rise from 0-16% of TLP to the top of the zone. Together this evidence indicates that deforested areas were becoming colonised by wild grasses, sedges and a diverse range of herb species common to disturbed ground.

Support for this interpretation is provided by the high numbers of Filicales and *Pteridium* spores in this zone. Further, the indeterminate pollen and charcoal curves show a great deal of similarity in trend with highly fluctuating values throughout the zone. The link between the appearance of *P. lanceolata* and *Pteridium* pollen, both indicators of disturbed ground, and anthropogenic activity is well established (Pennington, 1975; Caseldine, 1990; Mighall and Chambers, 1995). The charred particle peaks may also suggest increased levels of human induced burning episodes or camp fires (Patterson *et al.*, 1987).

Individually the decline in the tree and shrub pollen, the increase in herb pollen and peaks in charred particle values can be explained by natural changes in the vegetation and firing. However, the combination of all these factors taken with the indicator taxa for human disturbance prominent in the pollen sequence make anthropogenic activity the most probable cause for the dynamic changes in vegetation throughout the zone. The timing of the zone between *circa* 4,500 and 1,800 ^{14}C years BP further indicates this to be the case. If this interpretation is accepted then the minerogenic rich layers recorded in the lithostratigraphy can be explained.

Edwards *et al.* (1991) noted that deforestation has a significant influence on the geomorphological processes of the slope soils. At Brighouse Bay the result of this would have been erosion of the soils and their deposition in the valley bottom (i.e. the minerogenic rich layers). The increase in indeterminate pollen grains certainly supports this view implying sediment reworking and increased weathering. Similar examples of slope erosion resulting from the impact of prehistoric populations on the vegetation have been recorded elsewhere (Simmons *et al.*, 1975; Edwards *et al.*, 1991). If this is the case then the lack of cereal type pollen grains within this zone would point towards a pastoral subsistence. Indeed the existence of grazing livestock would doubtless enhance the extent and rapidity of deforestation and soil erosion. The possible marine provenance of the minerogenic layers is not supported by the pollen evidence.

In a steep valley sided location and a small catchment area such as that found at Brighouse Bay is an ideal location to record a very local pollen assemblage (see Tauber, 1965, 1967; Jacobson and Bradshaw, 1981). This combined evidence of lithostratigraphy, pollen and charred particle data in this zone all indicate this assertion to be the case at this site.

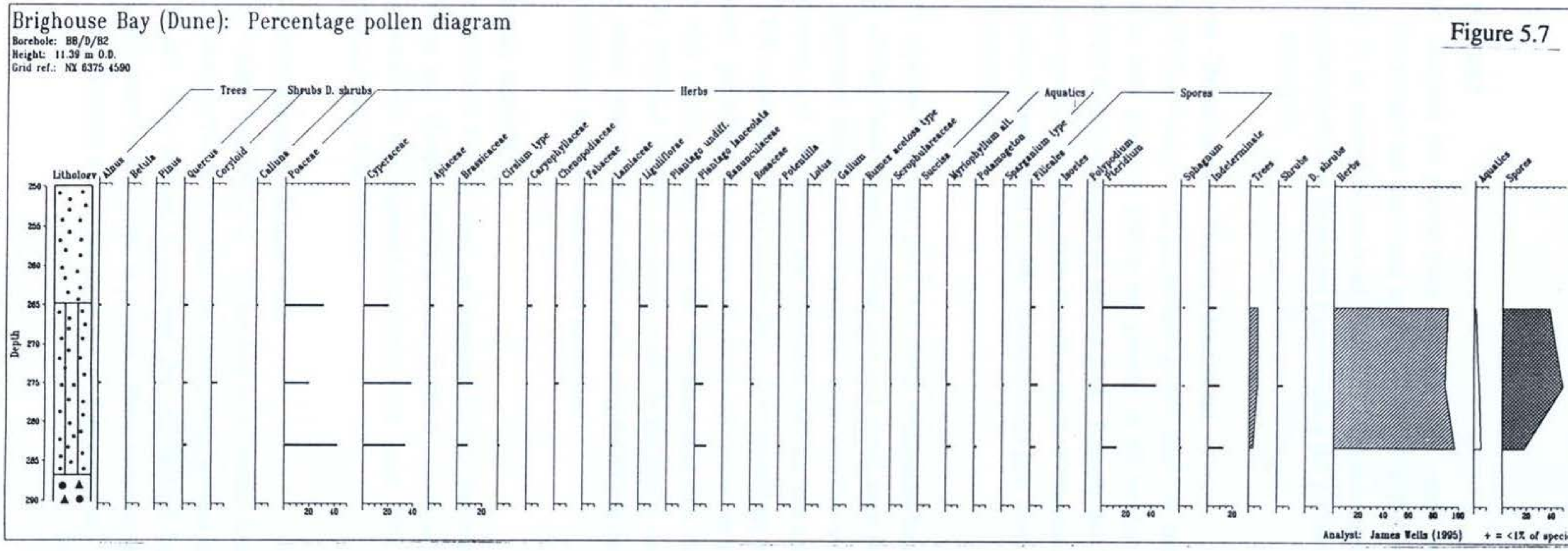
BB/POL/7 (8.53-9.20m O.D.)

This zone is characterised by low pollen values (<10% TLP) for the arboreal species, however, taxa including *Alnus*, *Quercus*, Coryloid and *Salix* all record a significant enough presence to suggest that small fragments of a mixed deciduous woodland still remained in the vicinity of Brighouse Bay. Also of note is the continued presence of *Calluna* in the first half of the zone: whether this dwarf shrub was present in Brighouse Bay or was a regional signature is difficult to ascertain. Herb pollen values (*circa* 85% TLP) and species diversity are high with Poaceae (>12% TLP) and Cyperaceae (>45% TLP) dominating. The common additional species, which were recorded in most levels, include Apiaceae, Asteraceae, Lactuceae, *P. lanceolata*, Ranunculaceae, *Filipendula*, Rubiaceae and *Rumex acetosella/acetosa*. The large grass pollen that are commonly termed 'cereals' record a noticeable presence in this zone. Although this occurence may represent some cultivation at Brighouse Bay it is considered here that these grains were probably a regional component of the assemblage rather than a local one. From this evidence it would appear that Brighouse Bay during this zone was an area of open meadow dominated by sedges and grasses with few trees and probably no cultivation.

Aquatic pollen record a marked peak in the first half of this zone (up to 23% TLP) with species present including *Typha* species, *Potamogeton*, *Myriophyllum* species and *Menyanthes trifoliata* but values fall by mid-zone. This probably indicates that the marshland area around the sample site was much wetter in the first half of this zone possibly with occasional standing pools on the bog surface. Spore values are low throughout although Filicales and *Pteridium* record a regular presence indicating their presence at Brighouse Bay - probably close to the damp area around the marsh.

Charred particles are at low levels, but indeterminate pollen grains do register significantly during the zone. This limited evidence probably implies that the charcoal in previous zones was indicative of the important role that anthropogenic firing of the woodland played during deforestation at Brighouse Bay.

Figure 5.7



Brighouse Bay (Dune): Percentage pollen diagram
Borehole: BB/D/B2
Height: 11.39 m O.D.
Grid ref.: NX 6375 4590
Trees
Shrubs D. shrubs
Herbs
Aquatics
Spores
Lithology
Depth
Alnus
Betula
Pinus
Quercus
Coryloid
Calluna
Poaceae
Cyperaceae
Apiaceae
Brassicaceae
Cirsium type
Caryophyllaceae
Chenopodiaceae
Fabaceae
Lamiaceae
Liguliflorae
Plantago undiff.
Plantago lanceolata
Ranunculaceae
Rosaceae
Potentilla
Lotus
Galium
Rumex acetosa type
Scrophulariaceae
Succisa
Myriophyllum alt.
Potamogeton
Sparganium type
Filicales
Isoetes
Polypodium
Pteridium
Sphagnum
Indeterminate
Trees
Shrubs
D. shrubs
Herbs
Aquatics
Spores
Analyst: James Wells (1995)
+ = <1% of species

5.4.3.2 Borehole: BB/D/B2

Three samples were analysed for pollen from the peat with sandy inclusions at location BB/D/B2. The results are presented in Figure 5.7. The formation of this deposit is not thought to be related to sea-level changes. This investigation was an attempt to estimate the timing of dune formation by correlating the pollen record from this location with that from T42.

Poaceae - Cyperaceae - Brassicaceae - *Plantago lanceolata*

No tree, shrub or dwarf shrub taxa record percentages greater than 5% throughout the assemblage. Of these only *Quercus* pollen are present in all levels. Herb taxa dominate this assemblage with percentages at around 90%. Poaceae and Cyperaceae values are the main taxa present, however, both Brassicaceae and *Plantago lanceolata* record relatively high percentages (*circa* 5-10%) throughout the peat layer. *Pteridium* spores are recorded in high numbers.

This evidence clearly represents an open grass and sedge dominated landscape with deforestation having already taken place. Those tree and shrub taxa that record a presence probably represent either small stands of trees locally or a regional component. The presence of *P. lanceolata* and *Pteridium* indicate that anthropogenic activity has affected the vegetation of Brighouse Bay. The assemblage is, however, barren in cereal pollen providing no support for local cultivation activity. This evidence combined with similar results from the T42 core may cast doubt on the evidence presented by Maynard (1994a) of plough marks in the buried soil layer (see section 5.2.2). The pollen assemblage correlates well with BB/P/7 in core T42 and would imply a post-2,000 ^{14}C years BP date for its formation.

5.4.3.3 Borehole: BB/F/B3

Although pollen analysis has already been undertaken on the foreshore peats at Brighouse Bay (Bishop and Coope, 1977) a more detailed investigation using a systematic sampling procedure was required for the present study. The diagram is presented in Figure 5.8 and described below.

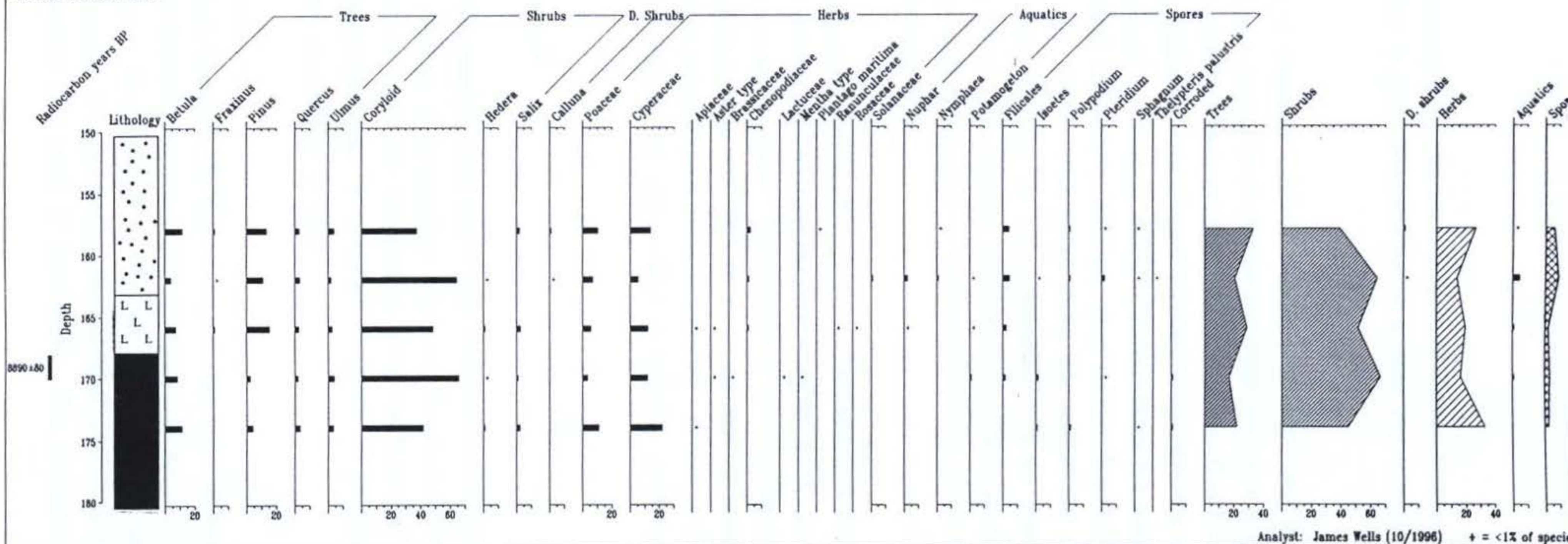
Coryloid - *Betula* - *Pinus* - Poaceae - Cyperaceae

Coryloid pollen values range from 40-65%. Of the tree taxa present *Betula c.*10%), *Quercus* (*c.*5%) and *Ulmus* (*c.*5%) percentages are consistently present in all levels. *Pinus* pollen values are also present throughout the assemblage but increase significantly in the upper three levels. *Salix* is present. *Alnus* is not recorded in any level. Of the herb taxa Poaceae and Cyperaceae are well represented. The upper

Brighouse Bay (Foreshore): Percentage pollen diagram

Figure 5.8

Borehole: BB/F/B3
Height: 2.25 m O.D.
Grid ref.: NX 63441 45376



three levels are distinguished by the consistent occurence of Chenopodiaceae in low percentages and an increase in spore (Filicales) and to a lesser degree aquatic taxa values.

The assemblage appears to represent a mixed woodland of hazel, oak, elm and possibly pine with locally open areas of low herb diversity stands dominated by grasses and sedges. No hiatus is implied by the assemblage. As outlined in section 3.3.8 high Chenopodiaceae and pine pollen are taxa commonly related to an increasing marine influence as a result of sea-level rise (Godwin, 1975). Chenopodiaceae are commonly, but not exclusively, coastal herb plants that can often tolerate brackish water conditions (Clapham *et al.*, 1987). Pine pollen grains are saccate and can be transported readily by water resulting an over-representation in an assemblage (Traverse and Ginsberg, 1966). The increase of Filicales and aquatic species may result from both a rising water table and/or an increased oceanicity of the climate during periods of relative sea-level rise.

If a marine provenance is accepted for the silty clay deposit (see section 5.4.4.2) then the contact between this unit and the underlying peat bed is suitable as an index point for a sea-level transgression in the region. The absence of *Alnus* pollen probably indicates that these sediments correlate with the lowermost peat beds that underlie the marls in borehole T42 which pre-date *circa* 7,600 ^{14}C years BP. A date of 8,890±80 ^{14}C years BP has been recorded for this contact in BB/F/B3 confirming this interpretation.

5.4.4 Foraminifera analysis

5.4.4.1 Borehole T42

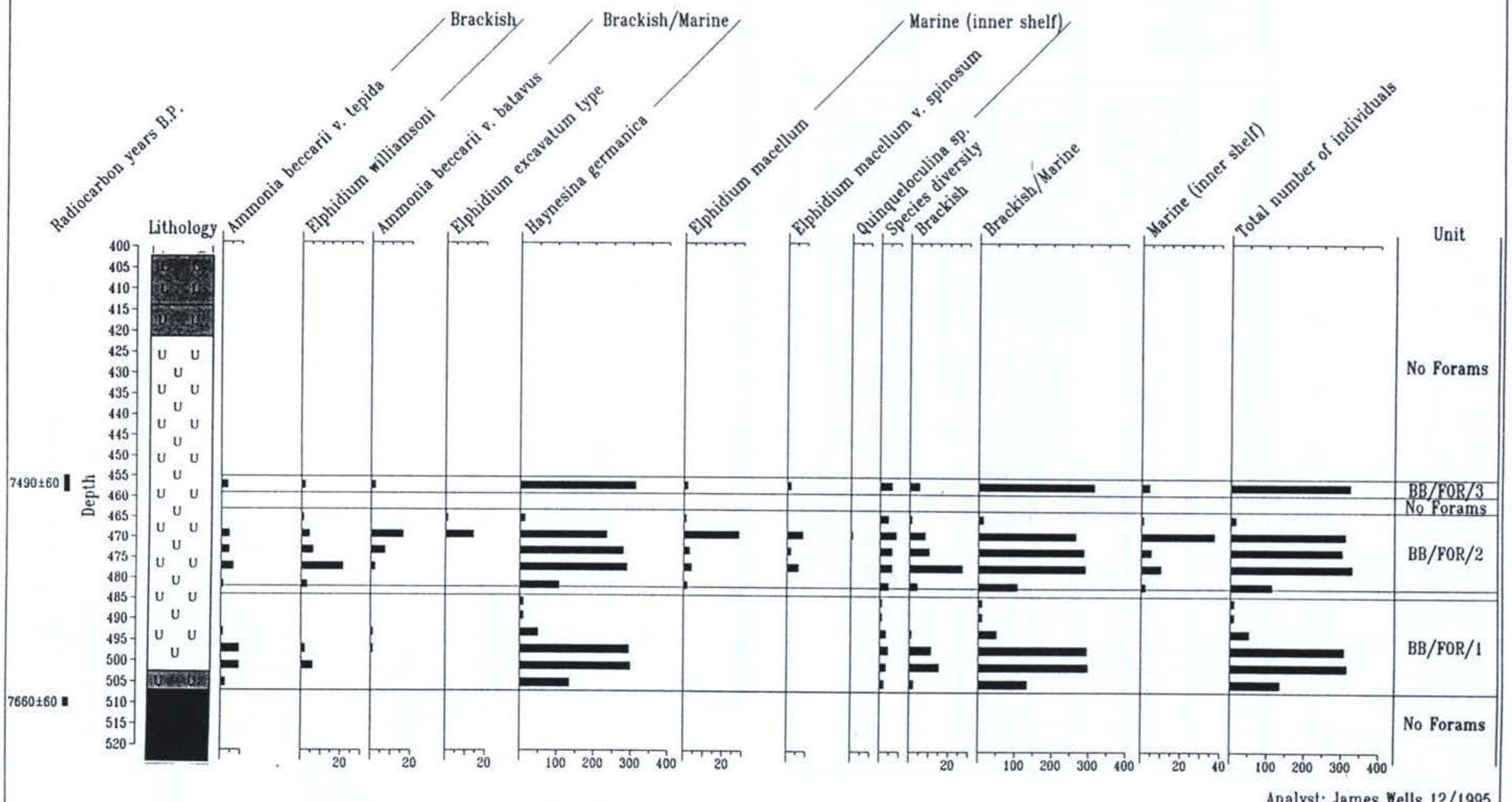
In total eight species of foraminifera, listed below, were identified from the sequence. Twelve levels contain evidence of foraminifera which can be divided into three separate units (BB/FOR/1-3) which are separated by levels where no foraminifera were present. The foraminifera data is presented in Figure 5.9 and the main characteristics of each unit are described in Table 5.3.

BB/FOR/1 (4.13-4.36 m O.D.)

The lowermost unit, which represents the base of the marl deposits, is dominated by the extremely euryhaline *Haynesina germanica* in all levels. In fact the upper two levels have only tentatively been assigned to this unit as species abundance and diversity is low (10 individuals of *H. germanica* were recorded each level) and may have been partially reworked as a result of bioturbation. The euryhaline species

Figure 5.9 Brighouse Bay: Foraminifera assemblage

Borehole: T42
Height: 9.20m O.D.
Grid ref: NX 263755 545982



T42 Foram. Unit	Altitude (m O.D.) Depth (cm)	Main characteristics of foraminifera unit
BB/FOR/3	**4.65-4.61** 455-459	***Haynesina germanica*** *H. germanica* dominates unit. Minor components of *Ammonia beccarii v. aberdoveyensis, Elphidium williamsoni, A. beccarii v. batavus, E. macellum* and *E. macellum v. spinosum.*
BB/FOR/2	**4.57-4.38** 463-482	***H. germanica - Elphidium sp. - Ammonia sp.*** *H. germanica* dominates unit. In the first half of the unit the brackish species of *E. Williamsoni* peaks at 475-479 cm before falling sharply to the upper limit. In the second half of the unit the brackish/marine and marine species increase. Peaks in representation of *A. beccarii v. batavus, E. excavatum, E. macellum* and *E. macellum v. spinosum* occur at 467-471 cm.
BB/FOR/1	**4.36-4.13** 484-507	***H. germanica - A. beccarii v. aberdoveyensis - E. williamsoni*** *H. germanica* dominates unit. From 503-495 cm get peaks in numbers of *H. germanica, A. beccarii v. aberdoveyensis* and *E. williamsoni.* Numbers of individuals in the uppermost levels (495-484 cm) are low.

Table 5.3 Characteristics of foraminifera units in borehole T42, Brighouse Bay.

Ammonia beccarii v. *aberdoveyensis* is present in low numbers for the lowermost part of this unit along with the brackish *Elphidium williamsoni* and the more marine *A. beccarii* v. *batavus*.

This association, with the possible exception of the latter species, is a common brackish lagoon association in estuaries around North West Europe and has been described by Murray (1991) from the Exe Estuary. The dominance of *H. germanica* could well indicate large fluctuations in the salinity of the water body (0-35‰). *E. williamsoni* certainly is common in shallow (<2m depth) and low energy water bodies (Richter, 1964). The low numbers of *A. beccarii* v. *batavus* may represent an allochthonous component as it is commonly associated with waters of higher salinities (Murray, 1979). In modern samples collected from the intertidal sand beach close to the low water mark at Brighouse Bay *A. beccarii* v. *batavus* comprises a much greater component of the total foraminifera assemblage (see Chapter 4). Indeed, the foraminifera assemblage recorded from a modern sample collected from an intertidal brackish pool on the salt marshes of the nearby Cree estuary has more in common with the association of this unit. The foraminifera microfauna of BB/FOR/1 is therefore taken to indicate a shallow, low energy, brackish lagoon/pond.

BB/FOR/2 (4.38-4.53 m O.D.)

This unit contains the most diverse fauna with all the species listed above present. *Haynesina germanica* continues to dominate, suggesting that the environment of deposition is that of a shallow, low energy, brackish lagoon/pond, with subsidiary specimens of *A. beccarii* v. *aberdoveyensis*, *Elphidium macellum*, *E. macellum* v. *spinosum*, *E. williamsoni*, and *A. beccarii* v. *batavus* also present. This assemblage, with the exception of *H. germanica*, suggests an increase in salinity levels as they are all typically species that tolerate more open marine conditions (Murray, 1979). Although these subsidiary species may represent an allochthonous component of the assemblage the individuals show no evidence of size sorting.

The spinose form of *E. macellum* is considered to be a trait of juveniles of this species and not a variant (Haynes, 1973). However, spines were identified on some of the largest specimens and none apparent on the more juvenile forms. It is probable that *E. macellum* was washed in from the open bay live and a small population was able to survive in the reduced salinity conditions of the brackish pond. It is suggested here that the spines developed on this species possibly as a result of physiological stress associated with salinity fluctuations. Support for this theory is provided by evidence from the Baltic Sea where species are well known to have been able to adapt to conditions of decreased salinity (see Murray, 1991).

BB/FOR/3 (4.61-4.65 m O.D.)

This final unit is comprised of only one sample. The association is as for BB/FOR/2 with *H. germanica* dominating, however, both *Elphidium excavatum* and *Miliolina* sp. are absent. The association is again interpreted as a shallow, brackish lagoon/pond. No foraminifera were found in the remainder of the shelly marl deposit nor in any other part of the T42 sediments.

Discussion

The presence of foraminifera species in the lowermost levels of the gyttja and marl deposits indicates that the development of a water body at Brighouse Bay is intimately linked with coastal evolution. How this water body relates to rising sea-levels and barrier formation is unclear. For a standing water body to exist in its fossil position, as delimited by the stratigraphical survey, would certainly have required the development of a barrier system. The existence of a barrier underlying the dune system has been identified in previous investigations and in the current stratigraphical survey (Borehole D/3).

The foraminifera identified could represent either a fossil population living in the water body or *post mortem* transport by the sea into the basin could have resulted in their incorporation into the sediment sequence. The broad range of *H. germanica* tests - the only species to be well represented in all levels - from juvenile to adult would indicate the former to be the most likely scenario. If this is accepted then the question of how saline water entered the basin is raised. Was there a direct link through low points in the barrier system or did marine water seep through the barrier? Did sea water only enter the system during the high point of spring tides or was the input a diurnal event? The answer to this issue can almost certainly not be established by the foraminifera evidence alone.

5.4.4.2 Borehole BB/F/3

In the one sample prepared for foraminifera analysis (30g wet weight of sediment) from the organic silty clays that overlie the peat beds a diverse foraminifera assemblage of 16 species was recorded. The results are presented below.

Species	Number of Individuals
Ammonia beccarii v. aberdoveyensis	5
Elphidium williamsoni	35
E. excavatum forma *lidoensis*	29
E. cf. *margaritaceum*	1
E. magellanicum	7
E. oceanensis	2
Haynesina depressula	14
H. germanica	217
Jadammina macrescens	3
Lagena clavata	1
Miliolinella subrotunda	2
Quinqueloculina bicornis v. angulata	5
Q. cliarensis	1
Q. lata	3
Q. seminulum	2
Trochammina inflata	1
Unknown	1
Total number of tests	329

Similar to the foraminifera units from the marls in borehole T42 this assemblage is dominated by *H. germanica* and unequivocally establishes the marine provenance of the fine particulate minerogenic sediments overlying the peat beds. The other major species present are *E. williamsoni*, *E. excavatum* forma *lidoensis* and *Haynesina depressula*. The combination of these species together would suggest an estuarine environment such as a low inter-tidal mudflat (Murray, 1991). The presence of the other species in low numbers is probably as a result of *post mortem* transport into the bay. Although allochthonous this component of the assemblage does indicate that contact with the open sea was strong and the presence of protective offshore barriers during deposition was unlikely. The two agglutinating species - *J. macrescens* and *T. inflata* - recorded may reflect the initial influence of the terrestrial peat beds as a substrate during minerogenic deposition.

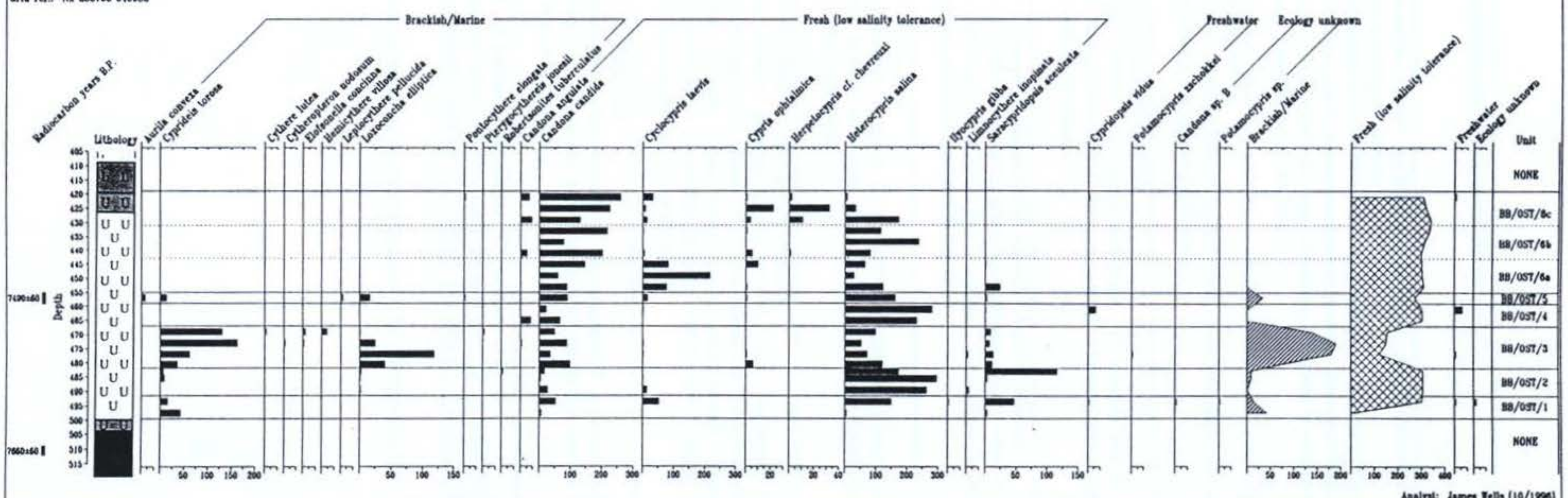
5.4.5 Ostracoda analysis

5.4.5.1 Borehole T42

Of the 23 samples prepared only two, the lowermost of the marl sequence, were barren. Twenty four species were identified in total with diversity ranging between 3 and 11 species for any one level. The faunal succession has been divided into six phases based upon variations in salinity fluctuations as indicated by the changing fauna. The uppermost phase (BB/OST/6) has been further sub-divided into three sub-zones where distinct changing faunal associations within a freshwater unit are visible. The results of the ostracod analysis are presented in Figure 5.10 and the main characteristics of each phase are described in Table 5.4. The population age structures of the three dominant species *Cyprideis torosa*, *Candona candida* and *Heterocypris salina* were determined and are presented in Figure 5.11.

Figure 5.10 Brighouse Bay: Ostracod assemblage

Borehole: T(4)2
Height: 9.20m O.D.
Grid ref.: NX 263755 545982



T42 Ostracod Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of ostracod phase
BB/OST/6c	**5.00-4.88** 420-432	***Candona candida - Heterocypris salina - Herpetocypris* cf. *chevreuxi - Cypria ophtalmica - Cyclocypris laevis*** *H. salina* dominates initially before falling in numbers to the top of the sub-phase. *C. candida* values synchronously increase to dominate the upper levels. Both *C. ophtalmica* and *H.* cf. *chevreuxi* peak mid-phase. *C. laevis* is present throughout the sub-phase, *Candona angulata* less so.
BB/OST/6b	**4.88-4.77** 432-443	***C. candida - H. salina*** *C. candida* dominates the bottom and top levels of the sub-phase with *H. salina* numbers increasing significantly mid-phase.
BB/OST/6a	**4.77-4.65** 443-455	***C. laevis - C. candida - H. salina*** A significant increase in *C. laevis* mid-phase. *C. candida* and *H. salina* are represented strongly throughout. Distinctive peak in *Sarscypridopsis aceuleata* in the lowest level of the phase.
BB/OST/5	**4.65-4.61** 455-459	***H. salina - C. candida - Loxoconcha elliptica - Cyprideis torosa*** This phase is based on one level where brackish and marine ostracod species are recorded - particularly *L. elliptica* and *C. torosa*. Nonetheless, *H. salina* and *C. candida* are the most well represented species.
BB/OST/4	**4.61-4.53** 459-467	***H. salina - C. candida*** *H. salina* dominates the phase. Low values of *C. candida*. *C. angulata* is present in the lowest level of the phase. The distinctly freshwater *Cypridopsis vidua* is recorded in the upper level.
BB/OST/3	**4.53-4.38** 467-482	***C. torosa - H. salina - L. elliptica - C. candida*** *L. elliptica* numbers increase sharply to peak mid-phase before dropping as quickly to the top of the phase. *C. torosa* values rise throughout the phase to dominate by the upper levels. Other marine species record a presence in the upper half of the phase. *C. candida*, *H. salina* and to a lesser degree *S. aceuleata* are all well represented throughout the phase.
BB/OST/2	**4.38-4.29** 482-491	***H. salina - S. aceuleata*** High numbers of *H. salina* throughout. Sharp peak in *S. aceuleata* in the upper limit of the phase. *C. candida* present in all levels but in low numbers. *C. torosa* recorded in uppermost levels.
BB/OST/1	**4.29-4.21** 491-499	***C. torosa - H. salina - S. aceuleata - C. candida - C. laevis*** High *C. torosa* values in lower half of phase which falls in upper half. The main species in the upper level are *H. salina*, *S. aceuleata*, *C. candida* and *C. laevis*.

Table 5.4 Main characteristics of ostracod phases in borehole T42, Brighouse Bay.

Figure 5.11a Cyprideis torosa: population structure (borehole T42)

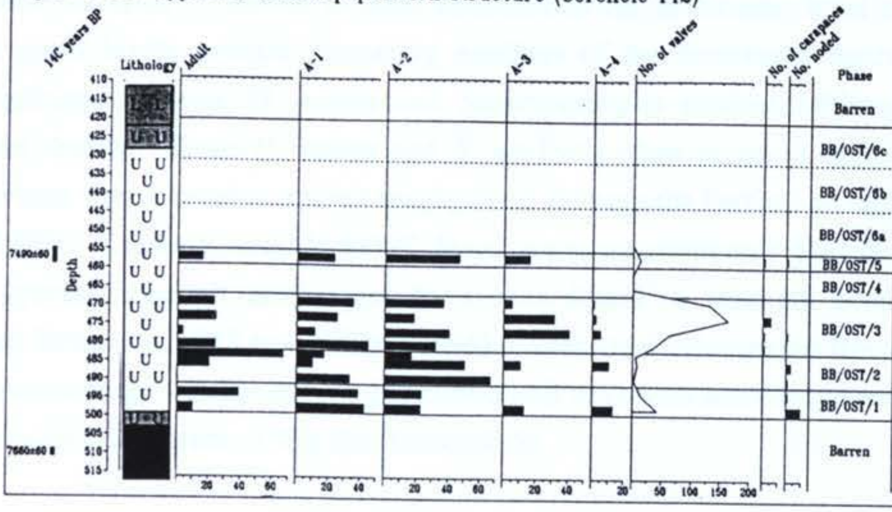


Figure 5.11b Candona candida: population structure (borehole T42)

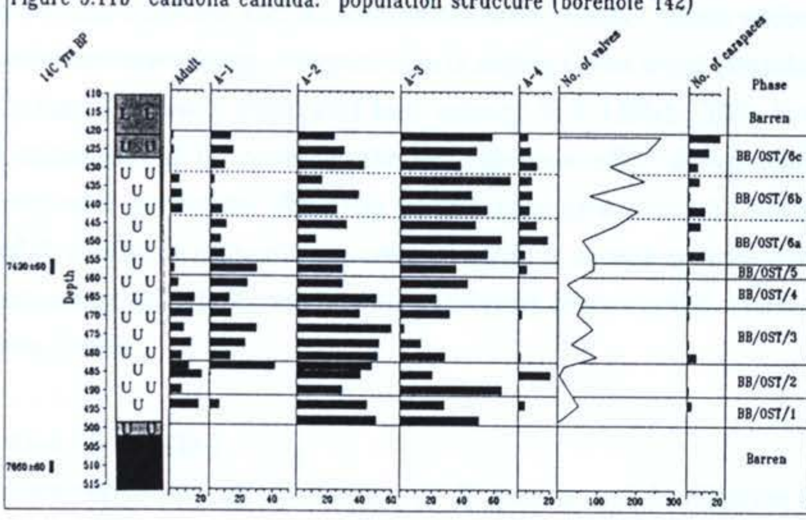
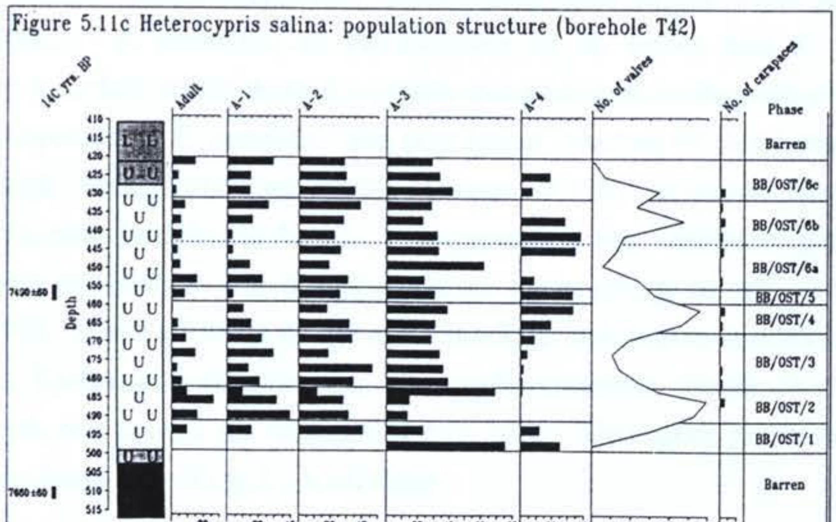


Figure 5.11c Heterocypris salina: population structure (borehole T42)



BB/OST/1 (4.19-4.31 m O.D.)

The euryhaline ostracod *C. torosa* is most abundant in the lowermost level of this zone. The upper levels contain increasing numbers of the freshwater species *C. candida*, *Cyclocypris laevis*, *H. salina* and *Sarscypridopsis aculeata* although *C. torosa* values decline. Both *H. salina* and *S. aculeata* often occur in mixohaline conditions where waters receive marine seepage (i.e. through the barrier) or salt spray (Griffiths, 1995). *Candona candida* and *C. laevis* are more commonly considered as freshwater species although both again have been found in brackish conditions (Forester and Brouwers, 1985 in Griffiths, 1995). Additional information from these species' known ecology would indicate a shallow, well vegetated and environmentally stable water body (Henderson, 1989; Griffiths, 1995).

BB/OST/2 (4.31-4.43 m O.D.)

This zone contains occasional worn individuals of marine/brackish species including *C. torosa*, *Loxoconcha elliptica* and *Robertsonites tuberculatus* which probably occur as a result of sediment reworking. *Herpetocypris salina* is the most abundant species and is presently found in water bodies of low salinity (0.4-13‰). This is reinforced by the limited occurence of *C. candida*, the near absence of *C. laevis* and a lack of halophilous freshwater ostracods. The top of this zone is marked by the significant reappearance of *S. aculeata* indicating increased salinity as this species has a known optimum salinity range of 5-10‰ yet is able to tolerate higher levels (40‰) for short periods (Griffiths, 1995).

BB/OST/3 (4.43-4.55 m O.D.)

This zone is characterised by an abundance of *C. torosa* and *L. elliptica* specimens indicating an increase in water salinity. These two species have been commonly found in a protected brackish/lagoonal environment such as the Fleet in Dorset (Whittaker, 1972). A reduction in the numbers of *H. salina* and *S. aculeata* individuals are recorded, whilst there is a synchronous increase in the purportedly less saline tolerant species of *C. candida* - the population structure of this latter species suggests a high energy thanatocoenosis (Figure 5.11b) probably representing reworking from elsewhere in the basin. Also present in the lowermost part of this zone is *Cypria ophtalmica* which may indicate a deepening of the water body (Griffiths, 1995). Small numbers of the more brackish and marine species including *Cythere lutea*, *Cytheropteron nodosum*, *Elofsonella concinna*, *Hemicythere villosa* and *Pterygocythereis jonesii* are recorded in this zone. Their poor preservation and low numbers indicate reworking from offshore.

BB/OST/4 (4.55-4.59 m O.D)

Brackish/marine species, including *C. torosa*, are absent and in its place *H. salina* dominates with low numbers of *Candona angulata*, *C. candida* and the exclusively freshwater form *Cypridopsis vidua*. This change clearly indicates the replacement of a brackish with an almost fresh water-body.

BB/OST/5 (4.59-4.67 m O.D.)

This zone sees a return to that assemblage described for BB/OST/3 with the reappearance of both *C. torosa* and *L. elliptica* (although not in such numbers as that previous zone). However, *H. salina* and *C. candida* numbers remain dominant. This might indicate that the marine influence was not as strong as in BB/OST/3 and BB/OST/1. Alternatively, and most probably, the episode of brackish water conditions may have been much shorter lived than the sampling interval (3cm thickness) allowed to constrain. Other freshwater species are poorly represented.

BB/OST/6a (4.67-4.82 m O.D.)

Cyclocypris laevis numbers increase sharply in this sub-zone and dominate the assemblage. This species is common in standing waters with vegetation (Fryer, 1985). In contrast the pattern of *H. salina* shows a decline in abundance which may result from the lowering water salinity and possible increase in aquatic vegetation. *Candona candida* remains ubiquitous.

BB/OST/6b (4.82-4.915 m O.D.)

The appearance of *C. ophtalmica* over the boundary between sub-zone 6a/6b also marks the end of *C. laevis* domination. *Candona candida* appears to show a fluctuating trend of increasing abundance throughout zone 6. *Heterocypris salina* increases to dominate the assemblage peaking mid-zone. This sub-zone correlates well with BB/OST/4, however, what this change in the ostracod assemblage represents is uncertain.

BB/OST/6c (4.915-4.995 m O.D.)

Initially *H. salina* values are high before falling at the top of the zone. *Candona candida* numbers continue to increase toward the top of the zone where it accounts for approximately 80% of the total population. The most characteristic aspect of this sub-zone are the consistant presence, albeit in low numbers, of *C. angulata*, *C. laevis*, *C. ophtalmica* and *Herpetocypris* cf. *chevreuxi*. The occurence of *C. angulata* is somewhat confusing as it is generally considered to be the more saline tolerant (up to 13‰) of the two *Candona* species present at this site. The latter three species indicate increasing vegetation (Griffiths, 1995). Above this zone peat deposits are present and ostracods are absent.

Overview

The migration of an ostracod community into this site occurs sometime after the establishment of foraminifera. The ostracod evidence indicates the presence of three periods of increased salinity and an analogous conclusion can be drawn from the foraminifera. A paucity of halophobous species and the dominance by species that can tolerate small amounts of salinity (oligohalobous halophilous) probably reflects the continued influence of sea water into the water body - possibly through sea-spray or water seepage during unusually high tides.

In addition to the information the ostracod analysis has provided for coastal evolution the data also offers some insights into ostracod ecological associations in coastal freshwater environments. A positive response of particular species, including *S. aceuleata* and *H. salina*, to phases of higher salinity levels is noticeable. The ability of *C. candida* to live in a water body during periods of relatively high salinity is clear although the species only flourishes after marine water inundations have ceased. It is probable that the near absence of halophobous species reflects the continued influence of the coastal location throughout the life of the permanent water body at Brighouse Bay. The paucity of investigations of marls (modern or fossil) from similarly situated coastal locations may account for the absence of records of *C. angulata* during the Flandrian. At the conclusion of the marl formation the ostracod fauna indicates an increasing organic content into the water body before an abrupt end to ostracod life at the site. The high numbers and dominance of *C. candida* in the uppermost level of the marl is testament to its ability to tolerate changing aquatic conditions. It is probable that the change from marl deposition to peat formation reflects either a hydroseral succession and/or a fall in relative sea level.

5.4.5.2 Borehole BB/F/3

From the same sample used for foraminifera analysis 23 ostracod species were identified and are listed below.

Species	Number of individuals
Aurila convexa	2
Cyprideis torosa	4
Cythere lutea	1
Cytherura gibba	1
Elofsonia baltica	4
Hemicythere villosa	9
Heterocypris salina	5
Hirschmania viridis	17
Leptocythere castanea	15
L. lacertosa	3
L. tenera	4
Loxoconcha elliptica	4
Nannocythere pavo	2
Palmoconcha guttata	2
P. laevata	3
Paradoxostoma ensiforme	1
P. normani	1
Sarscypridopsis aculeata	1
Sarsicytheridea bradii	2
Sclerochilus contortus	2
Semicytherura cornuta	1
S. nigrescens	2
S. sella	2
Unknown	2
Total number of valves	***90***

The main species recorded were *H. viridis*, *L. castanea* and *H. villosa*. The valves and carapaces recovered for *H. viridis* and *L. castanea* were present in both adult form and as juvenile instars. Low numbers prevent the assumption that these species formed the biocoenosis at this location from being made. Excluding *S. aculeata* and *H. salina*, both of which are more commonly regarded as freshwater species that can tolerate low salinity levels (Griffiths, 1995), all the other species are ostracods that are found in estuarine and brackish waters around the present coastline of the British Isles (Athersuch *et al.*, 1989). Again low numbers of all species indicate that *post mortem* transport was responsible for their deposition at this location. Undoubtedly, however, the minerogenic sediments were deposited in a brackish water/estuarine environment with close proximity to the open sea.

5.4.6 Mollusca analysis

5.4.6.1 Borehole T42

Samples were prepared for molluscan analysis from the sample core (T42) that visibly contained a significant shell content. All molluscs and marine shells (excluding foraminifera and ostracoda) were identified and have been grouped according to salinity tolerance. The mollusca have been divided into 6 phases based upon variations in salinity as indicated by the changing faunal assemblages. The final freshwater phase has further been separated into 4 sub-phases on the same basis. The results are presented in Figure 5.12 and the main charcteristics of each phase/sub-phase are detailed in Table 5.5.

BB/MOL/1 (4.13-4.25m O.D.)

No freshwater molluscs exist in this phase which is dominated by *Hydrobia ulvae* with a later occurrence of *Cerastoderma edule* and a presence of *Littorina littorea*. The latter two species are marginally marine. *Hydrobia ulvae* is a brackish species that can tolerate a salinity range of 5-40‰ and which thrives particularly on sand banks and amongst weeds of salt marshes (Cherrill and James, 1985). This species' optimum salinity is, however, approximately 15-20‰ (D. Keen, pers. comm.) and correlates well with the minimum salinity of 20‰ for *C. edule*. The low occurence of *L. littorea* may indicate an allochthonous component of the assemblage washed in from the bay. The environmental requirement for a firm, rocky substratum supports this suggestion and probably indicates marine waters were entering the system through breaches in the barrier or overtopping as opposed to water movement percolating through the barrier system.

BB/MOL/2 (4.25-4.41m O.D.)

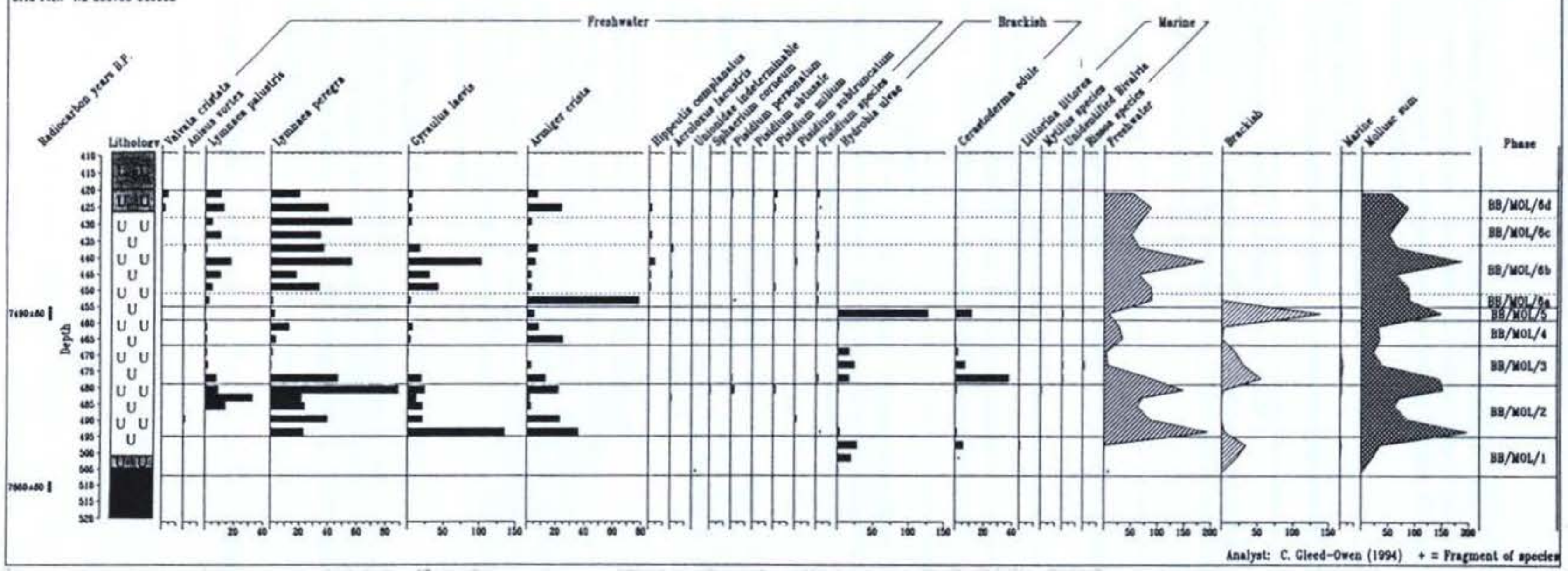
The brackish/marine species are replaced by a relatively diverse (11 species) pond dwelling freshwater assemblage dominated by *Gyraulus laevis*, *Armiger crista*, *Lymnaea peregra* and *Lymnaea palustris* - all species that prefer both a water body rich in macrovegetation and a muddy substrate. Initially *G. laevis* numbers are high indicating the possible presence of residual salinities (2-3‰) in the water system before the ubiquitous *L. peregra* values increase to dominate the phase.

BB/MOL/3 (4.41-4.53m O.D.)

In this phase there is a sharp revertance to brackish and marine species with the return of *H. ulvae* and *C. edule*. Of these two species *C. edule* is initially well represented before falling in the uppermost levels of the phase; *H. ulvae* is present at constant levels throughout. This may reflect early high salinities (>20‰). Two other marine species (*Rissoa* sp. and Unidentified bivalvia) are also present in low numbers which probably represent an allocthonous component. Initially the freshwater species of *L. peregra*, *G. laevis*, *A. crista* and *L. palustris* all remain present at high values in the lowermost level - possibly due to the broad sampling interval rather than an indication that the species were living at the same time. For the remainder of the phase these species record either very low numbers or a complete absence indicating possible reworking (e.g. bioturbation; tidal water disturbance) of individuals from below or above.

Figure 5.12 Brighouse Bay: Mollusc diagram

Borehole: T42
Height: 9.20m O.D.
Grid ref.: NX 263755 545982



Analyst: C. Gleed-Owen (1994) + = Fragment of species

T42 Mollusc Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of mollusc phase
BB/MOL/6d	**5.00-4.92** 420-428	***Lymnaea peregra* - *Lymnaea palustris* - *Armiger crista*** *L. peregra* dominates sub-phase. *L. palustris* and *A. crista* are both represented in low numbers. Additional species present include *Valvata cristata*, *Gyraulus laevis* and *Pisidium* sp..
BB/MOL/6c	**4.92-4.84** 428-436	***L. peregra* - *L. palustris*** *L. peregra* dominates sub-phase. *L. palustris* is represented in low numbers.
BB/MOL/6b	**4.84-4.69** 436-451	***L. peregra* - *G. laevis* - *L. palustris* - *A. crista*** The two species *L. peregra* and *G. laevis* dominate sub-phase. *L. palustris* and *A. crista* are consistantly present. All of these species (excluding the latter) peak in abundance at 439-443 cm.
BB/MOL/6a	**4.69-4.65** 451-455	***A. crista*** *A. crista* dominates sub-phase. *L. palustris*, *L. peregra*, *G. laevis* and *Pisidium* sp. all record a low presence.
BB/MOL/5	**4.65-4.61** 455-459	***Hydrobia ulvae* - *Cerastoderma edule*** The brackish species *H. ulvae* and to a lesser degree *C. edule* dominate this phase. Low numbers of freshwater species are also present.
BB/MOL/4	**4.61-4.53** 459-467	***A. crista* - *L. peregra*** The lowermost level of the two that comprise this phase is dominated by *A. crista* albeit in low numbers. In the upper level *L. peregra* increases in presence. *L. palustris* and *G. laevis* also record a presence in this unit.
BB/MOL/3	**4.53-4.41** 467-479	***C. edule* - *H. ulvae*** In the lowermost level of this phase there is a mixture of the freshwater (*L. peregra*, *G. laevis*, *A. crista*, *L. palustris*) and brackish species (*C. edule*, *H. ulvae*). Mid-phase the freshwater species fall sharply in numbers as does *C. edule*. *H. ulvae* remains constant throughout.
BB/MOL/2	**4.41-4.25** 479-495	***L. peregra* - *G. laevis* - *A. crista* - (*L. palustris*)** A peak of *G. laevis* in the lowermost level of this phase falls sharply to a constant low level in the remaining levels. *A. crista* also peaks at the same point but falls in numbers more steadily before an abrupt rise in the top level of the phase. *L. peregra* is represented consistantly throughout the phase although it also records a sharp peak in the uppermost level. In the second half of the phase *L. palustris* appears.
BB/MOL/1	**4.25-4.13** 495-507	***Hydrobia ulvae*** *H. ulvae* is the only species represented in all levels of this phase. The inclusion of the lowermost level is based on a single occurrence of that species. The upper limit of the phase records the presence of *C. edule* and the appearance of *Littorina littorea*.

Table 5.5 Main characteristics of mollusc phases in borehole T42, Brighouse Bay.

BB/MOL/4 (4.53-4.61m O.D.)

An abrupt return to freshwater species is marked by the near complete absence of brackish/marine taxa. *Lymnaea peregra* and *A. crista* values, however, are low. Of these two species the latter one appears to recolonise and dominate first. *Gyraulus laevis* and *L. palustris* are also present in low numbers. The environmental interpretations are similar to phase BB/MOL/2.

BB/MOL/5 (4.61-4.65m O.D.)

The third brackish/marine phase is characterised by high values of *H. ulvae* with approximately 120 individuals counted. *Cerastoderma edule* is also present in relatively high numbers and may imply a direct contact with the sea - whether by barrier breaching or overtopping is impossible to establish. The freshwater species of *L. peregra, G. laevis* and *A. crista* all record a very low presence in this phase and probably represent a reworked component from above and/or below the sediment.

BB/MOL/6a (4.65-4.69m O.D.)

The final phase which continues until the top of the lacustrine marl sediments is devoid of brackish/marine species. This sub-phase comprises only one level in which *A. crista* values (*circa* 75 individuals) dominate completing a familiar pattern to the sequence of this species' apparent ability to colonise the water body after brackish conditions end. *Gyraulus laevis*, *L. peregra*, *L. palustris* and *Pisidium* sp. are all present in low numbers.

BB/MOL/6b (4.69-4.84m O.D.)

Armiger crista which dominated the last sub-phase has fallen to low values, but is nonetheless recorded in every level. *Lymnaea peregra* numbers rise sharply at the bottom of the zone and the species continues to be well represented throughout. *Gyraulus laevis* values also increase peaking in the upper half of the sub-phase with approximately 100 individuals recorded before dropping markedly in the upper most level. The presence of this species in such numbers may reflect a slight increase in salinity levels, but not necessarily so. Numbers of *L. palustris* similarly increase to peak at the same point and then drop in the upper most level. Of the other freshwater species recorded from this sub-phase *Hippeutis complanatus* are present most regularly. The presence of this species may reflect an increase in water body size but is certainly indicating the richness of macrovegetation in the pond.

BB/MOL/6c (4.84-4.92m O.D.)

Lymnaea peregra numbers dominate this sub-phase. *Lymnaea palustris* and, to a lesser extent, *A. crista* are also present in low numbers. The environmental significance of this assemblage does not suggest different aquatic conditions from the previous freshwater phases. It is possible that the near absence of *G. laevis* is reflecting the absence of any residual salinities and may indicate that the exclusion of a marine influence into the pond may be complete.

BB/MOL/6d (4.92-5.00m O.D.)

Lymnaea peregra remains dominant in this sub-phase but records a distinctive decline in numbers from the previous sub-phase. *Armiger crista* values initially peak before falling back in the upper most level. *Lymnaea palustris* continues to be represented. *Gyraulus laevis*, *Valvata cristata* and *Pisidium milium* are all recorded throughout the sub-phase - *V. cristata* noteably for the first time in the assemblage. The presence of the latter two, eutrophic, species probably indicates an increase in aquatic macrovegetation and shallowing of the water body to <1m depth (Walker *et al.*, 1993). These changes are undoubtedly signaling the infilling of the basin during the final stages of hydroseral succession as indicated by the lithostratigraphic transition to organic rich silts.

As was recorded in the foraminifera and ostracod assemblages the three brackish phases are well represented here also. That the environment was a small, muddy bottomed, shallow pond is implied from the molluscan evidence.

5.4.7 Foraminifera and ostracod analysis of the foreshore red/pink silty clay

The red/pink silty clays with some stones that were recovered from the spoil of the gas pieline excavations were prepared (30g wet weight) for foraminifera and ostracod analyses. The results are as follows:

Foraminifera	
Ammonia beccarrii v. *batavus* Hofker	6
Elphidium excavatum f. *clavata* Cushman	146
Elphidium williamsoni Haynes	4
Elphidium magellanicum Heron-Allen and Earland	3
Globulotuba sp. nov. (3) Jones	2
Haynesina germanica (Ehrenberg)	9
Haynesina orbiculare (Brady)	3
Polymorphina type	2
Total	**175**

Ostracoda	
Sarsicytheridea punctillata (Brady)	101 (of which 7 were carapaces)
Total	**101**

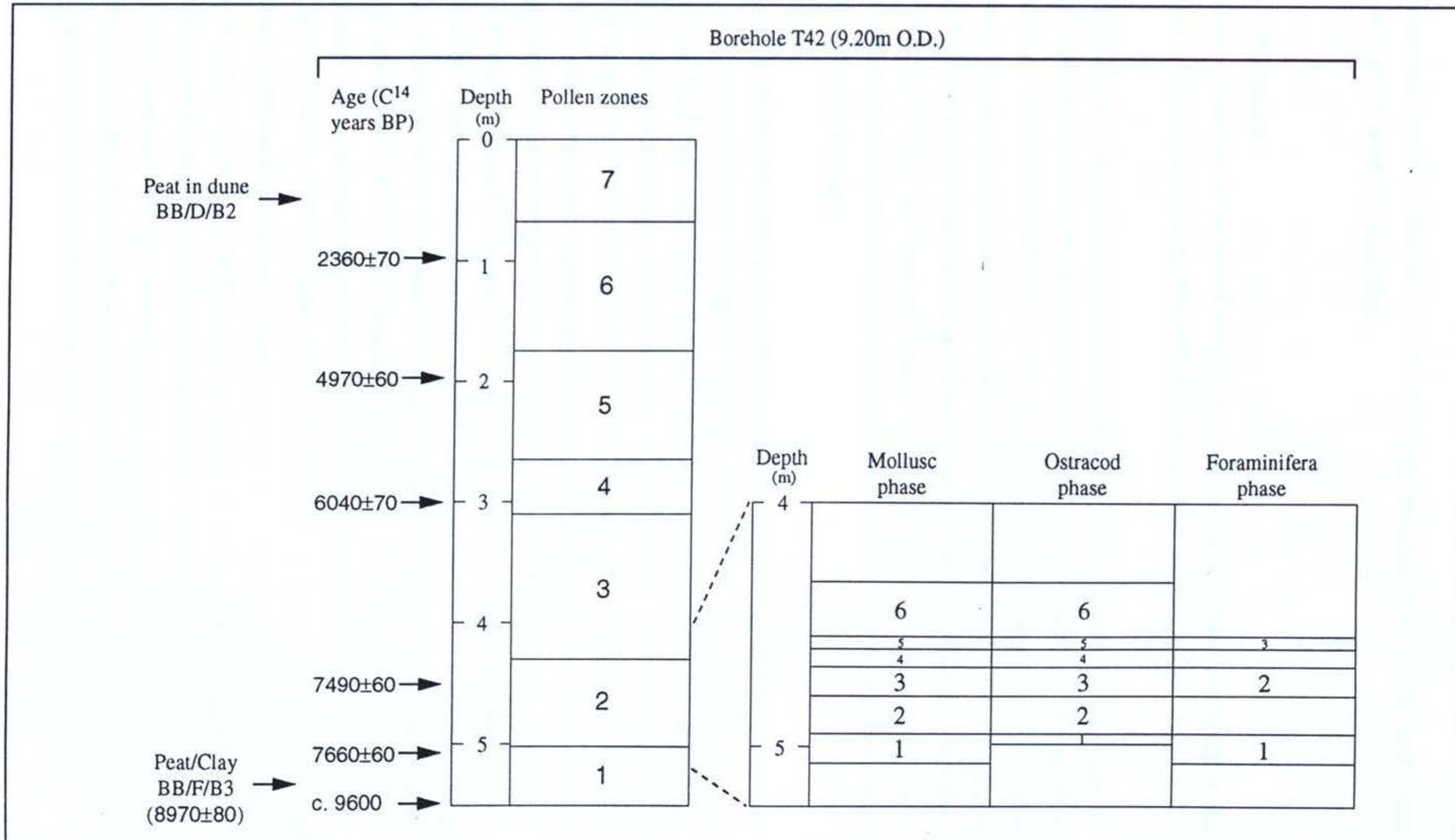


Figure 5.13 Palaeoenvironmental zone/phase correlations for borehole T42 and probable age correlations with boreholes BB/D/B2 and BB/F/B3 (Brighouse Bay)

Mollusca were rare in the sediments with only occasional juveniles and some fragments which were not identified.

5.5 Discussion

A summary diagram is provided that links all microfossil zones/phases from the borehole T42, borehole stratigraphy and radiocarbon dates (Figure 5.13).

The red/pink silty clay sediments are stratigraphically unconstrained but probably lie beneath the non-fossiliferous blue/grey diamict that is overlain by the foreshore buried peat. The similarities between the microfauna from these sediments, which indicate a boreo-arctic marine depositional environment, and those of the Lateglacial Clyde Beds found elsewhere in Scotland (see Peacock, 1981) are striking. No dates have been undertaken on these sediments to confirm this. If this correlation is accepted then these would be the first confirmed record of the Clyde Beds equivalents in the Solway Firth region.

Although a radiocarbon date has not been acquired for the lowermost peat contact with the non-fossiliferous blue/grey deposits in the T42 borehole the pollen assemblage from this basal peat and that from the foreshore borehole (BB/F/3) - which is also underlain by a similar diamict - correlate well. Logically these peat deposits appear to be of the same stratigraphic context and, although not proven, possibly underlie the dune system and buried barrier beach - if not eroded at that location during barrier construction. The date of 9,640±180 ^{14}C years BP on the foreshore peat (Bishop and Coope, 1977) combined with those from T42 indicate the existence of a near complete Flandrian vegetational history from the sediments lying behind the dune system. A marked alder rise immediately prior to the marine fossil bearing marl deposits is dated at 7,660±60 ^{14}C years BP. The pollen assemblage from the foreshore peat and overlying marine muds (altitude of contact 0.58 m O.D.) show no presence of alder. Clearly, with a date of 8,890±80 ^{14}C years BP, the foreshore sequence records an earlier stage of marine transgression prior to the deposition of the brackish marls. There is a difference in altitude of *circa* 3.6m between the two sedimentary units but this value does not account for the altitude of the fossil barrier which must have dammed the water body that deposited the marls. Importantly, the foreshore radiocarbon date on the peat which underlies the estuarine sediments can be used as an index point for the development of a regional relative sea-level curve.

Muds were deposited during the early Flandrian in the foreshore at Brighouse Bay where medium and coarse sands now comprise the intertidal zone. Perhaps the stream running out into the bay played a more significant role in the past, equally the influence of the nearby estuarine environments of Kirkcudbright Bay, Fleet Bay and/or Wigtown Bay may have provided the finer minerogenic sediment source. The increase in particle size may be more a reflection of changing wave energy rather than sediment supply. Alternatively the silts and clays may have been reworked from a source further offshore.

The inherent problems of understanding fossil barrier formation and the relationship of the sediments formed behind such a system makes interpretation complex. For a small brackish pond to have formed in the area behind the dune/fossil barrier system (as indicated by the marl sequence) the development of a barrier system is essential. That the initiation of marl deposition is contemporaneous with the fossil barrier system is further emphasised by the marine/brackish water subfossil (foraminifera, ostracod and mollusc) evidence from the lowermost of the marl sediments. Understanding the growth and evolution of the buried fossil barrier system is made all but impossible by the sand covering it. For this reason the suggestion that the three phases of brackish water sediment deposition within the marls represents three transgressive/regressive phases of the sea is not plausible. More likely is that the two latter brackish layers indicate stages of barrier breaching or a regular flow of seawater through the barrier into the newly formed basin. With a date of 7,490±60 ^{14}C years BP for the final brackish stage of the marl deposits the total time period for barrier construction - up to a height where it excluded any later breaches by the sea - was approximately 200 years. This date was, however, undertaken on marine shells which would have had an old carbon content in the calcium carbonate of the shells (see 3.4.7). A date some 425 years younger at *circa* 7,100 ^{14}C years BP probably times the end of brackish water marl deposition at Brighouse Bay.

If it can be logically assumed that the maximum Flandrian relative sea level in this area resulted in the construction of the barrier beach system then the dates from the brackish marl deposits may record the culmination (maximum lateral extent) of the Main Postglacial Transgression. This is not to suggest, however, that the sea then fell immediately but could have remained at a stable level relative to the land for some time after. Ultimately the use of the dates as index points in constructing a relative sea-level curve for the Cree estuary region is not possible due to the poor altitudinal control allowed by the barrier system but they do offer a datum point for other locations which may also record the maximum of the Main Postglacial Transgression at this time.

The alder rise has often been correlated with the rising Flandrian sea-level where slightly brackish and wetter conditions (afforded by increasing oceanicity of the climate) favour the species and result in the decline of those taxa that prefer drier conditions such as *Salix* (e.g. Smith, 1984). At Brighouse Bay this relationship appears unequivocal with the alder rise coinciding precisely with the first brackish unit recorded behind the barrier system. The date of *circa* 7,600 ^{14}C years BP for this event would also make it one of the earliest occurences of the alder rise in Scotland (Smith, *op cit*). By contrast, however, the pollen evidence from the foreshore peats and overlying silty clay show no evidence for the presence of alder. This contact clearly charts an early stage in the rise of Flandrian sea levels in the area. Therefore the alder rise at this location - and possibly at other similar coastal sites - should perhaps more accurately be equated with the culmination of the Main Postglacial Transgression.

Following the end of the marl formation terrestrial peat deposits (some minerogenic content) form behind the barrier system with a pollen assemblage indicating a mixed deciduous woodland dominated by alder, oak and hazel. The peat is briefly interrupted by a sand layer (aeolian) the upper limit of which has been dated at 6040±70 ^{14}C years BP. This deposit may well be the first major stage of dune development in the bay.

Between approximately 7.4 and 8.2m O.D. the peat deposits are separated by clay layers. These have been dated as occurring between 4,970±60 and 2,360±70 ^{14}C years BP. The stratigraphic relationship within the basin is not clear. The layers in borehole T42 were investigated and contained no evidence that they were deposited under marine conditions as was initially considered. The detailed pollen investigation of these sediments reveal falling tree and shrub values in combination with rising herb values (no cereals) and marked peaks in spores, indeterminate pollen grains and charcoal values. Of particular significance was the consistent levels of *Plantago lanceolata* (Ribwort plantain) through the sequence which is well established as an indicator of disturbed ground (e.g. Godwin, 1975). The pollen and charcoal records indicate that human impact - probably initiated during the Neolithic and continuing until the Roman occupation - through deforestation of the valley sides at Brighouse Bay have led to the destabilisation of slope soils and resulted in inwashing of minerogenic material into the valley bottom.

The pollen assemblage from the uppermost layers of the sequence indicate a grass and sedge dominated landscape. Sandy inclusions within the organic rich deposits suggest further dune growth/movement during the last 2,000 ^{14}C years. The pollen record from the buried organic rich deposit underlying dune sand and overlying the buried barrier beach indicates that it was formed during a time when the area would have been dominated by a herb-dominated vegetation with very few arboreal species. This would also reinforce the suggestion that further aeolian sand deposition occured sometime after *circa* 2,000 ^{14}C BP.

5.6 Summary of sea level research at Brighouse Bay

Stratigraphical investigations of this coastal valley mire which lies behind a stabilised dune system have identified a complex sequence of intercalated minerogenic and peat deposits. In addition the existence of a fossil raised barrier beach underlying the dune system has been reconfirmed as have the peat beds that lie underneath the intertidal sands. Pollen and charcoal analysis on core T42 has established that a near complete Flandrian vegetational record (probably reflecting very local changes) exists in the sediments from behind the dune system including considerable evidence for human impact and slope destabilisation. Pollen, foraminifera and ostracod analyses on the intertidal peats overlain by a silty clay (borehole BB/F/3) has established that the rising Flandrian sea level transgressed the peat sometime after 8,900 ^{14}C BP and, further, identified its contemporaneity with the lowermost peat deposits of the core T42. Detailed foraminifera, ostracod and mollusc analyses throughout the marl deposits in T42 have complemented each other in identifying three distinct phases of sedimentation where a marine influence into the lacustrine environment was significant enough to allow lagoonal conditions to persist. These layers have been dated as occuring between *circa* 7,700 ^{14}C BP and *circa* 7,100 ^{14}C BP. At no time since did the Flandrian sea penetrate behind the barrier system.

One further development has been the positive identification of the ostracoda *Candona angulata* from Flandrian sediments - its presence during this period having been previously unconfirmed (Griffiths and Evans, 1995).

Chapter 6 Cree estuary: morphology and stratigraphy

6.1 Introduction and background information

6.1.1 Site and situation

Wigtown Bay (Figure 6.1) is the outlet for the River Cree. Approximately 1km south-east of Newton Stewart the River Cree becomes tidal, with extensive estuarine muds and sands. The flat lowlands between Newton Stewart, Wigtown and Creetown - an area of relict fine grained estuarine deposits (carselands) overlain in places by Flandrian peats - are dissected by the River Cree. The surface altitude of the carselands that flank the Cree Estuary lies between 6 and 10m O.D.. Immediately to the west of this area are gently undulating hills that rarely rise above 50m O.D.. The eastern side of the carselands is flanked by steeply rising terrain which in places (*circa* 1 km from break of slope) can exceed 200m O.D..

6.1.2 Previous sea level studies

W.G. Jardine undertook research on former sea levels in the SW Scotland and concentrated much effort on the Cree estuary/Wigtown Bay region. Boreholes sunk (locations not provided) by Jardine (1975) to depths of up to 12m failed to reach the base of these sediments. He also reported that foundations for a (now disused) railway viaduct across the River Cree (NX 435 634) rest on rock 25m below the top of the raised estuarine deposits. In the valley of the Palnure Burn, however, the variably thick carse deposits never exceeded 7m and rest on fluvio-glacial sands and gravels. The details and results of this work are published in Jardine (1975) and have been summarised in sections 2.4.3 and 2.4.4 of this thesis.

The indicative meaning of each of the index points obtained as a result of Jardine's research in the Cree estuary region has already undergone critical analysis (see section 2.4.6; Haggart, 1982, 1989). But perhaps of greater concern was the methodology employed to achieve those results. It is hard to ascertain how systematic the lithostratigraphic survey across the carselands and overlying peats were. At Palnure, the only site where a cross-section of boreholes was detailed (Figure 8 in Jardine, 1975), the previous assertion that boreholes were sunk to a depth of 12m is true for just one borehole at this location. There is no indication that a programme of borehole transects was carried out at any of the other sites investigated. Indeed a number of the sites sampled for radiocarbon analysis appear to be from closer to the centre of the valley (e.g. Muirfad Flow, Baltersan). It was hoped that through the more detailed investigations of this study, presented in the following sections, the data

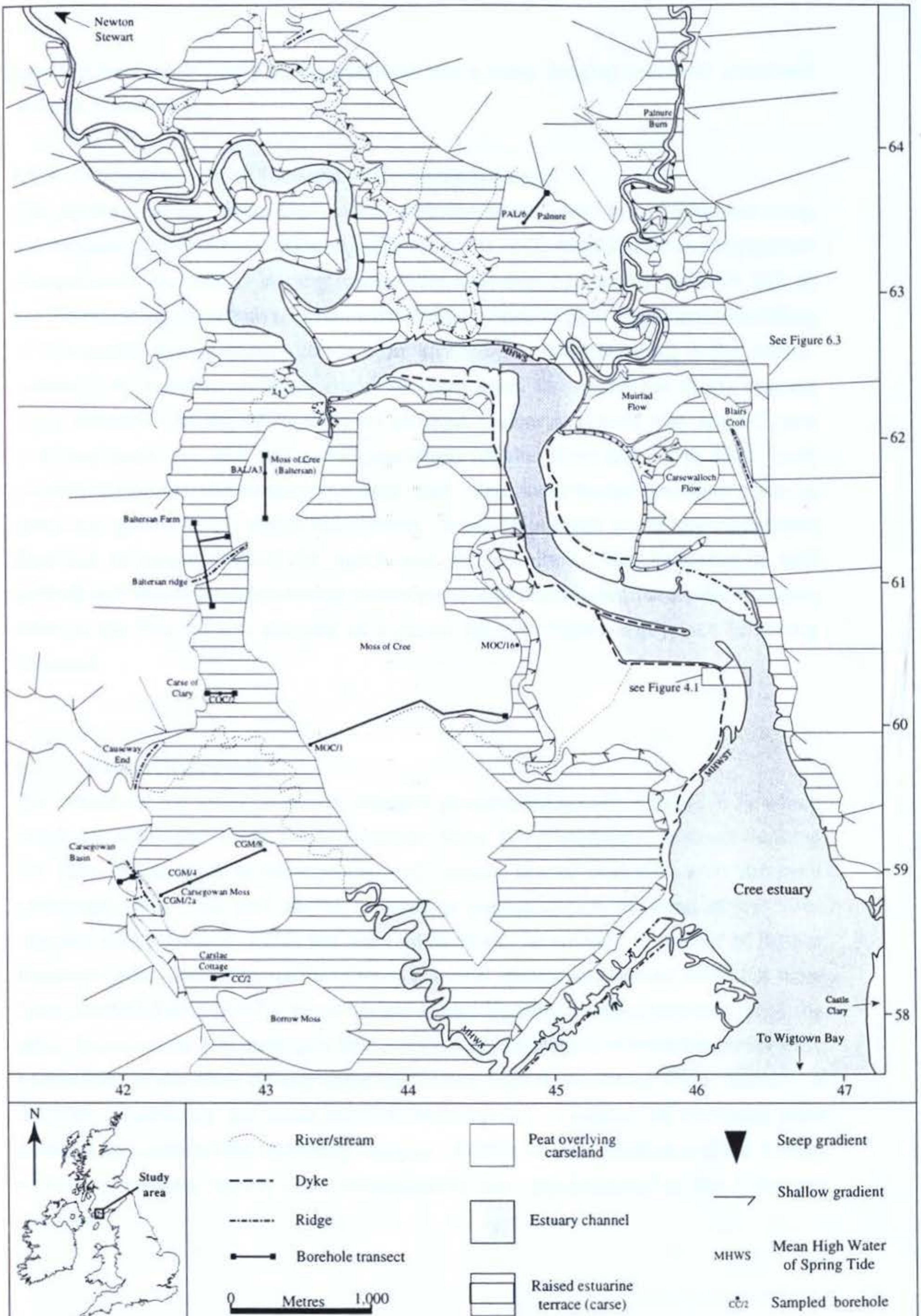


Figure 6.1 Cree estuary (SW Scotland): Geomorphological map and borehole transect locations

provided by Jardine could be incorporated into a more detailed sea level orientated research framework.

6.1.3 The gas pipeline (Scotland to Northern Ireland)

The pipeline was laid down from east to west across the Cree valley. Deep trenching was exposed at the eastern valley edge (Blairs Croft - NX 464 623) where the pipeline changed from the steeply sloping valley sides underlain by bedrock at Blairs Hill to the flat raised estuarine surfaces of the carselands. Prior to pipe laying and backfilling of this trench an opportunity to view the stratigraphy was presented to the author. Although no samples or levels could be taken from the trench for safety reasons (approximately 5m depth) in the time allowed a clear sequence was seen of peat overlying carse clay with two buried peat layers (neither more than 0.5m thick) lying respectively within and beneath the carse unit. The lower buried peat layer rests on sands and gravels below which lies bedrock. It was impossible to see any more detail than this as examination of the trench was not permitted. The existence of well defined and extensive intercalating minerogenic and organic sediments did however indicate the Blairs Croft location as a prime site for further study (see following sections).

6.2 Research strategy

The whole of the study area was mapped geomorphologically (Figure 6.1) which aided site selection. There are in excess of 30 sq. km of carseland deposits flanking the Cree estuary and in consequence only widely spaced transects were surveyed stratigraphically. As part of the research a reinvestigation of some of the sites reported on by Jardine (1975) has been undertaken. In addition a number of further locations with good potential for relative sea-level change and coastal evolution have been identified as part of a more extensive and detailed stratigraphic survey of the area. In excess of 300 boreholes (see Appendix E for details of each borehole) were undertaken in the Cree estuary carseland region with a maximum depth reached of 19.57m. Following the stratigraphical investigation a number of locations were selected and sampled for laboratory analysis. Details of each location and the results of the stratigraphic survey from representative sites are presented in the following sections.

6.3 **Palnure** (NX 450 636)

6.3.1 Introduction

The only transect of boreholes detailing stratigraphy in the Cree Estuary carseland area was presented by Jardine (1975) from Palnure (NX 450 636) where it was demonstrated that the peat deposits are lens shaped and overlie raised estuarine sediments up to the break of slope at the valley side. A sample borehole taken from this location by Jardine recorded 4.73m of peat overlying the estuarine deposits, the junction of these sediments being at 6.38m O.D. and radiocarbon dated to 6,480±107 ^{14}C years BP (Jardine, 1975). This was also the deepest borehole of those cored at this site and records the estuarine sediments as overlying bedrock at *circa* 0.5m O.D.. No evidence is presented for buried peat layers at this site.

In the present research a transect of boreholes from the valley edge toward the valley centre was undertaken. The objective of this programme of work was to reconfirm and expand upon Jardine's earlier findings. In total six boreholes were undertaken which varied in depth from 6.0m to 12.76m. One representative borehole (Palnure 6) was sampled for laboratory analysis and radiometric dating.

6.3.2 Lithostratigraphy

Figure 6.2 records the stratigraphy from the transect of boreholes undertaken at Palnure. The lens shaped peat beds recorded by the earlier research (see above) is demonstrated. The junction of the surface peats and the underlying carse sediments in all but borehole 6 is at approximately 8m O.D.. This altitude for the contact between the peat and carse differs markedly from the 6.38m O.D. radiocarbon dated contact of Jardine's (1975) Palnure borehole. That the carse surface is highly variable at this location is indicated by the North-South transect of Jardine (*op. cit.*).

In the borehole closest to the valley side (PAL/1) peat overlies the raised estuarine fine grained sediments which in turn would appear to rest on solid bedrock. Further from the valley edge, however, five boreholes record the presence of a dark brown well humified compact buried peat layer below the carse sediments. The junction of these deposits falls in height from *circa* -0.5m O.D. to -1.5m O.D. over approximately 100m toward the valley centre. This layer was only penetrated in PAL/5 and PAL/6 and a lower fine grained minerogenic layer was recorded beneath the buried peat - the two boreholes indicate the peat layer to be thinning toward the valley centre. The contact between the buried peat and the lower buried minerogenic sediments is at *circa* -1.5m O.D.. Equipment limitations meant that the full thickness of the lower minerogenic sediments was not established.

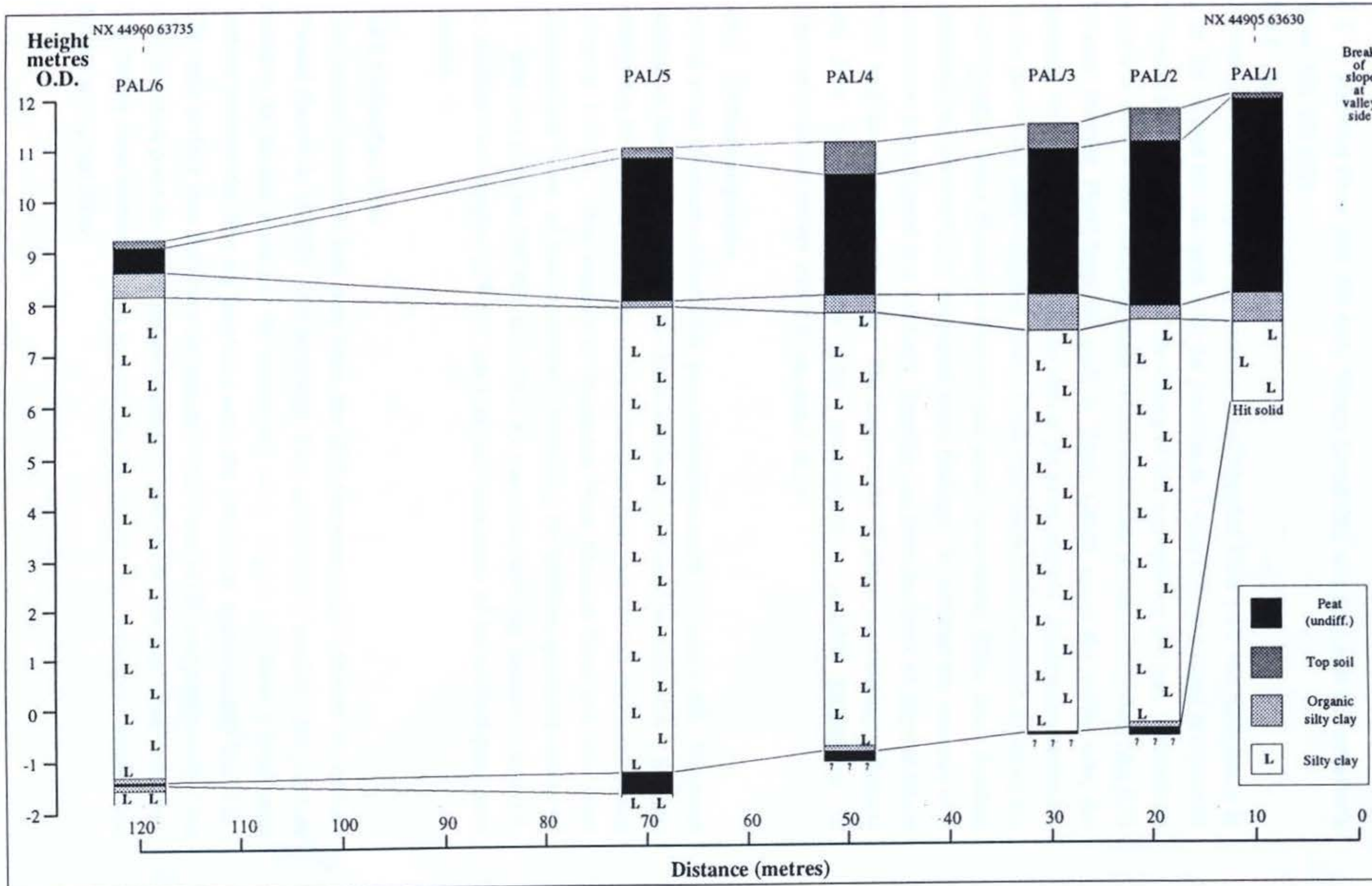


Figure 6.2 Palnure: Lithostratigraphical cross-section

6.4 Muirfad Flow (NX 456 625), Blairs Croft (NX 463 620) and Carsewalloch Flow (NX 459 617)

6.4.1 Introduction

Jardine (1975) investigated one location from Muirfad Flow (NX 453 620) where at least 3m of peat rest on carse with the junction at 7.92m O.D. and dated at 4,746±50 ^{14}C years BP which would record the timing of the regression at this site. For such an extensive area of peat overlying carse, which continues almost undisturbed (the A75 dissects Muirfad Flow from the peat in Blairs Croft) up to the valley side, the potential for sea-level research in this area is yet to be realised. Preliminary boreholes at the previously uninvestigated Blairs Croft (the north field) revealed evidence for interdigitating layers of carse sediments into peats close to the valley side. Pipeline trenching (see section 6.1.3) supported these findings. In addition the presence of a distinctive ridge aligned in a northerly direction out from the break of slope at Blairs Croft was identified (Figure 6.3). The complexity of these intercalating sediments and their relationship to the ridge necessitated a detailed programme of lithostratigraphical survey which is presented below.

6.4.2 Lithostratigraphy

In total seven transects of boreholes were undertaken north of Blairs Croft. The most detailed of these (transects 4-7) are presented here. It should be noted that it was not practicable to core down to the buried compact peat layer in all boreholes along transects 5 to 7. One transect of boreholes from Muirfad Flow and two from Carsewalloch Flow are also presented. Following the lithostratigraphical survey of this area two samples (BC/4/2 and CWF/A) were recovered for laboratory analysis. In addition two samples (CWF/1 and CWF/6) were taken of the surface peat/carse contact.

6.4.2.1 Muirfad Flow

The transect presented here runs from the A75 (borehole MF/1) toward the estuary channel (borehole MF/10). All boreholes were undertaken to establish the junction between the surface peats and the underlying carse. Figure 6.4 shows a level carse surface between the first six boreholes with the junction at approximately 9m O.D.. The carse surface then falls between borehole MF/6 and MF/8 to approximately 7.3m O.D. at which point the carse surface appears to level out for the final three boreholes. The falling carse surface altitude recorded in this transect may represent a lower carse terrace at Muirfad Flow.

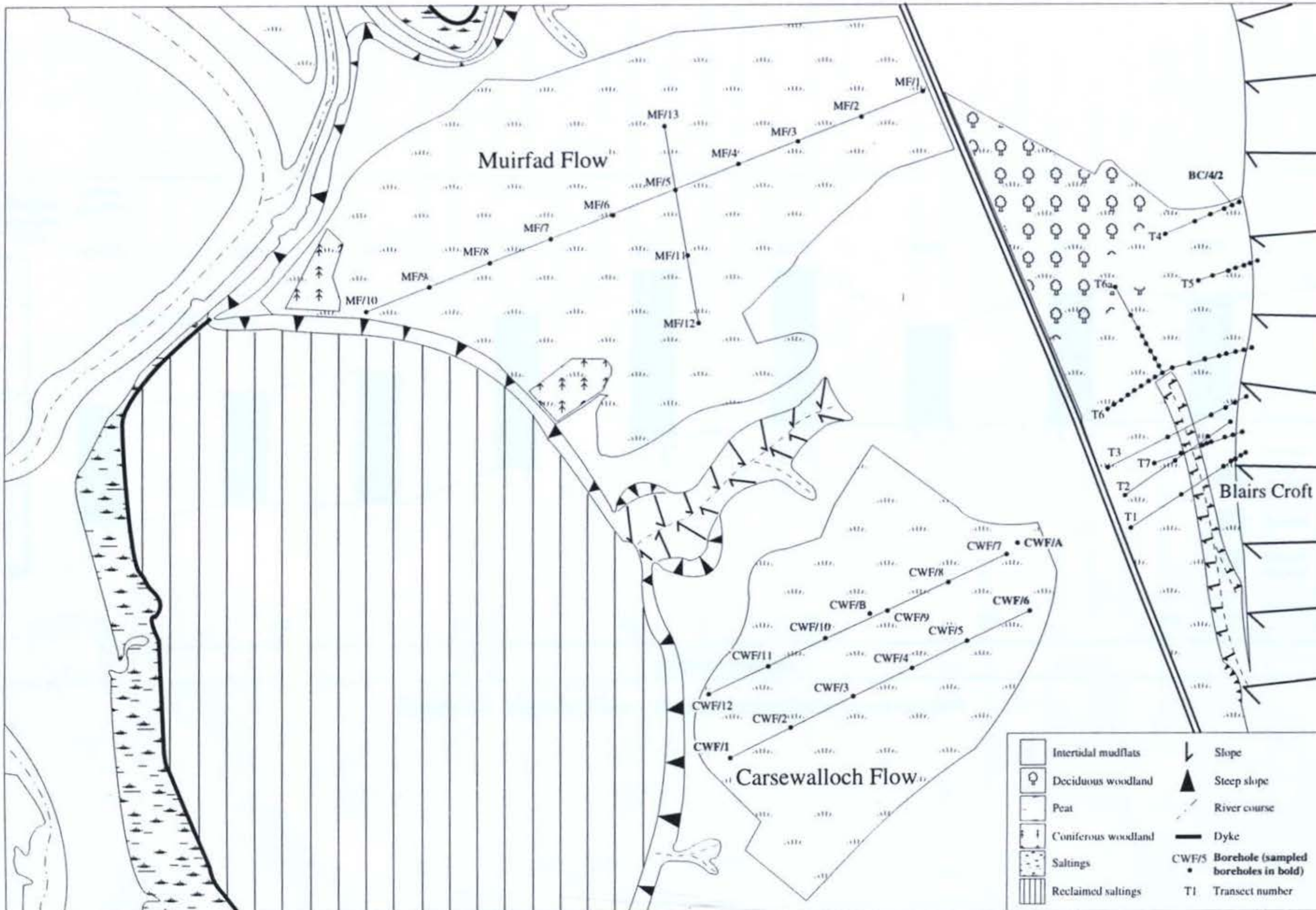


Figure 6.3 Blairs Croft, Carsewalloch Flow and Muirfad Flow: Geomorphological map and borehole locations

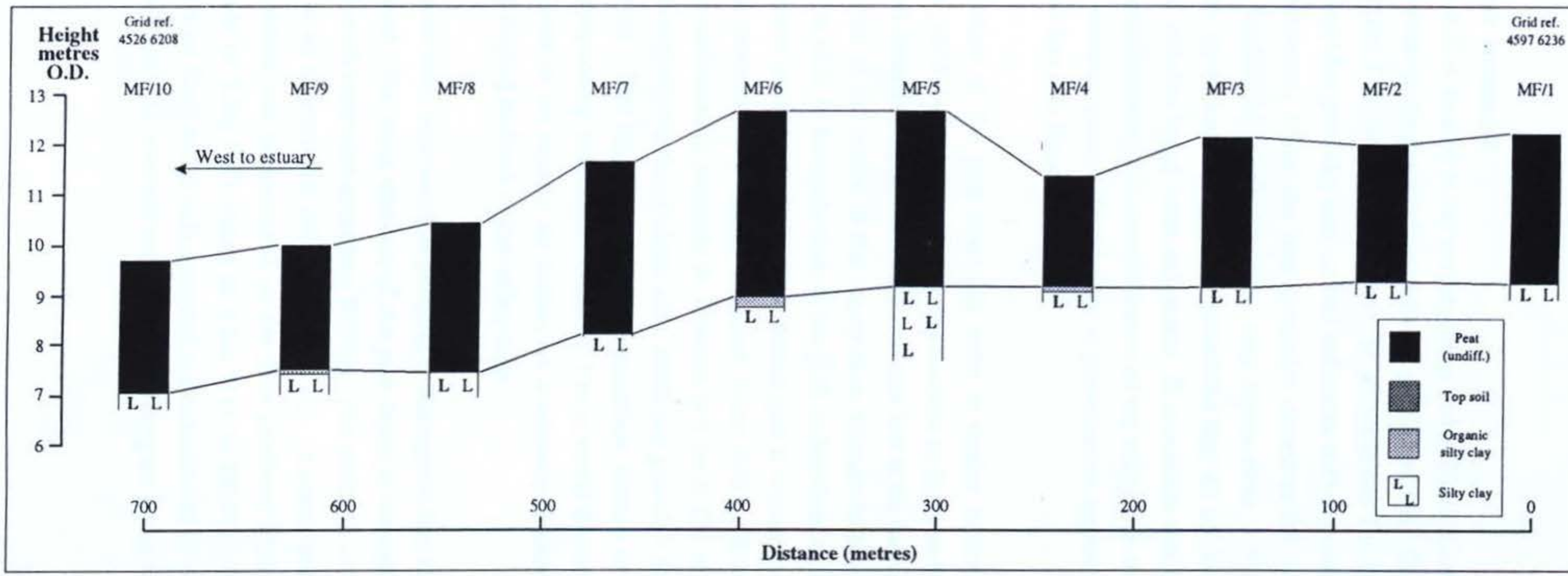


Figure 6.4 Muirfad Flow: Lithostratigraphical cross-section

6.4.2.2 Blairs Croft: transect 4

Transect 4 (Figure 6.5) is located at the northernmost end of Blairs Croft and is close (*circa* 10m) to the route of the gas pipeline and runs parallel with it. The peat surface is approximately 9.8m O.D. for all boreholes. In all boreholes the surface peat is recorded as overlying blue/grey silty clay (carse) sediments with a contact boundary at *circa* 8m O.D.. However, within the four boreholes closest to the valley edge the surface peats are broken by distinctive silty clay layers *circa* 8.5m O.D.. The provenance of these layers has not been determined but they do not stratigraphically appear to correlate with the lower carse sediments. It is possible that they represent slope wash sediments following soil destabilisation of the valley side that could have resulted from the anthropogenic deforestation; a phenomenon apparently identified nearby at Brighouse Bay (see Chapter 5).

The lens-shaped nature of the peat overlying carse is similar to that described at Palnure by Jardine (1975) but not recorded at that location in the present survey. The carse overlies a dark brown compact well humified peat bed at the base of each of the four boreholes closest to the centre of the valley at an altitude falling steadily from approximately -0.2m O.D. in borehole 3 to -0.6m O.D. in borehole 6. Evidence that minerogenic sediments underlie the lowermost buried peat is limited to the silty clay deposits that were recorded in borehole 3 (*circa* -0.6m O.D.). Buried peat also underlies the carse sediments in borehole 2 (junction at 1.2m O.D.) which is in turn underlain by a minerogenic matrix of clays, silts, sands and gravels - interpreted here as weathered bedrock. The high altitude of the peat/carse contact in this borehole relative to the corresponding contact in boreholes 3 to 6 would further indicate that the buried peats closer to the estuary are resting on a relatively horizontal sub-strate and not the steeply sloping bedrock of the valley sides.

Within the main carse unit, however, it is possible to distinguish four silty clay layers intercalated with peat. The most obvious of the peat layers is the uppermost and is probably recorded in all boreholes excluding BC/4/6. The thickness of this peat layer is variable but is at an approximate altitude of 7m O.D.. A lower peat layer is less extensive but its traces can be recorded in the four landward boreholes with an approximate altitude of 5.5m O.D. rising to 6.5m O.D. in BC/4/1. The third peat layer is very thin (*circa* 5cm) and is only recorded in two boreholes (2 and 3) and falls from 3.5m O.D. to 2.5m O.D. over the ten metres separating the boreholes.

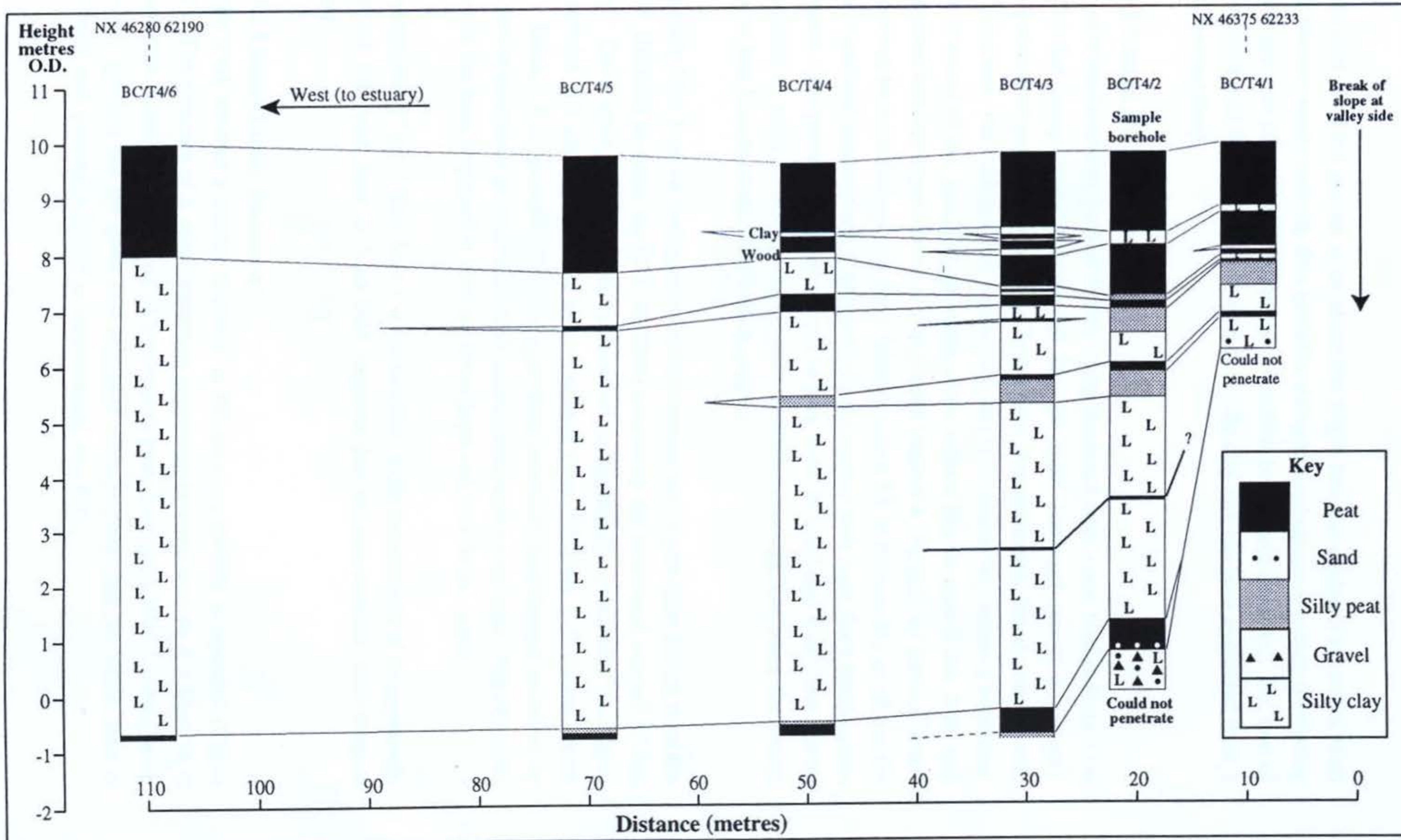


Figure 6.5 Blairs Croft Transect 4: Lithostratigraphical cross-section

If the silty clays are proven to be of marine origin then the evidence presented from this transect would indicate four probable transgressive/regressive events (excluding any suggestion of a shoreline below the lowermost buried peat deposits). For ease of correlation with the following transects each silty clay unit has been numbered from 1 to 4 (earliest first).

6.4.2.3 Blairs Croft: transect 5

In the seven boreholes (surface height rising landward from *circa* 10m O.D. to 11m O.D.) that comprise this transect all but the most landward record a complex intercalation of peats and silty clays (Figure 6.6). Approximately 2m of peat deposits overlie carse - the evidence for slope wash layers is limited in this series of boreholes. The junction of the overlying peat and carse surface lies at around 8m O.D. and correlates with the upper contact of Unit 4 from transect 4. Further, the base of Unit 4 is marked by a continuous peat layer (altitude range 7.5 to 6.6m O.D.) in all but the most landward borehole and corresponds to the similar peat layer from the previous transect. The presence of a less extensive peat layer in boreholes 4 to 2 can not be correlated so easily. These two layers have therefore been separated using the coding system into Unit 4a (lower) and Unit 4b (upper).

Similarly Unit 3 can be distinguished in this transect with a peat layer falling from 6m O.D. (BC/5/2) to *circa* 5m O.D. (BC/5/6) delimiting the lowermost contact of this unit. Once again, however, the presence of an apparently widespread peat layer (boreholes 2-7 and a respective fall in altitude from 6.5-5.4m O.D.) complicates correlation. It is possible that the apparently unrelated peat deposit recorded in BC/4/3 at an altitude of *circa* 6.5m O.D. corresponds to this peat layer. Thus the term Unit 3a has been employed to code the lower layer and Unit 3b the upper.

Distinguishing Unit 2 from Unit 1 is not so clear. Only the presence of an apparently isolated, thin peat layer at 3.2m O.D. suggests that the two separate intercalations exist.

6.4.2.4 Blairs Croft: transect 6

In the sixth transect a similar sequence to the previous transect is recorded (Figure 6.7). The presence of a more distinctive separation between Unit 4a and Unit 4b is marked as is the now clear layer of intercalated peats separating Unit 2 from Unit 1. Of less certainty are the peats that separated Unit 3a from Unit 3b which now is probably only present in BC/6/5 at approximately 6m O.D..

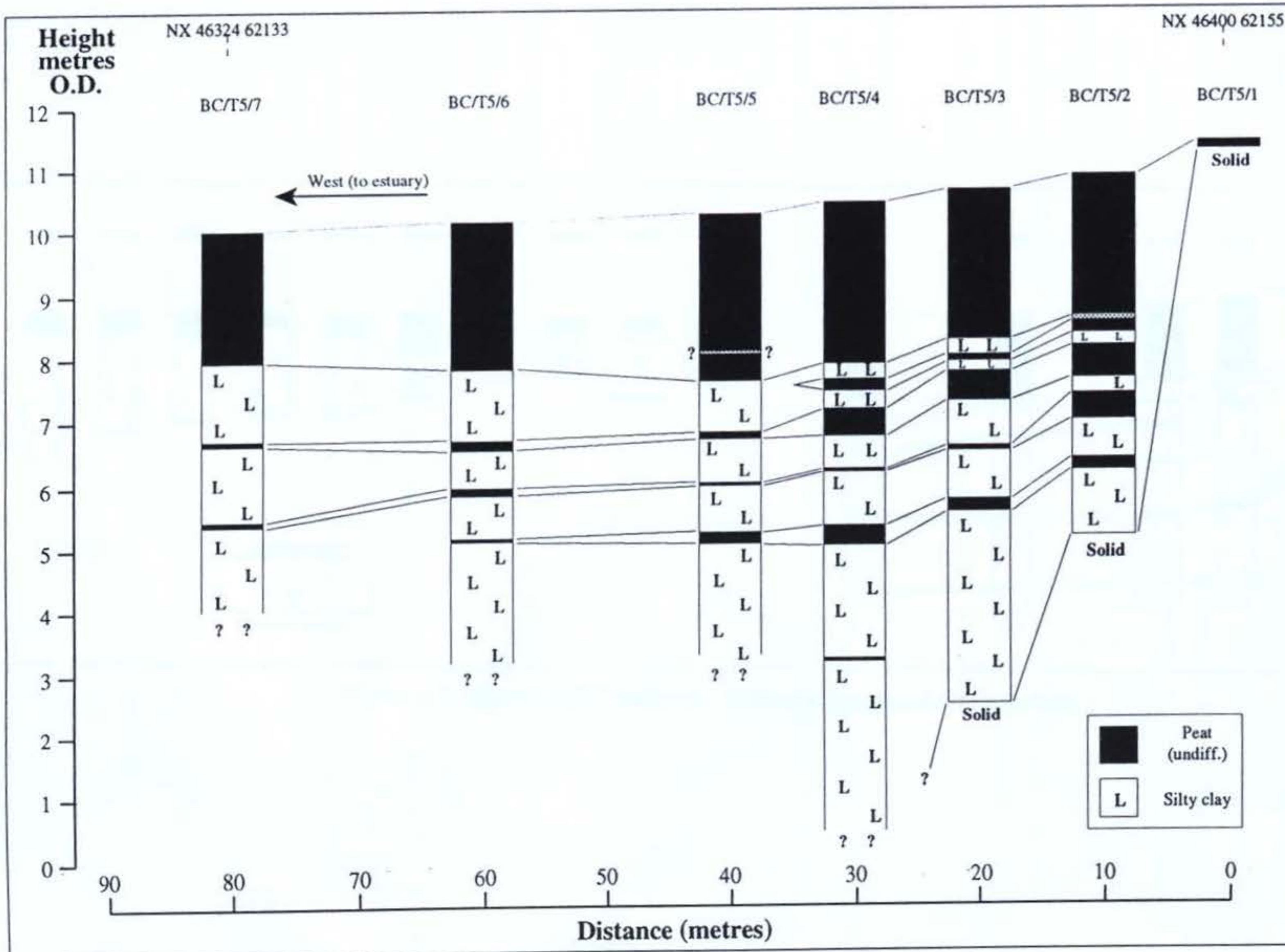


Figure 6.6 Blairs Croft Transect 5: Lithostratigraphic cross-section

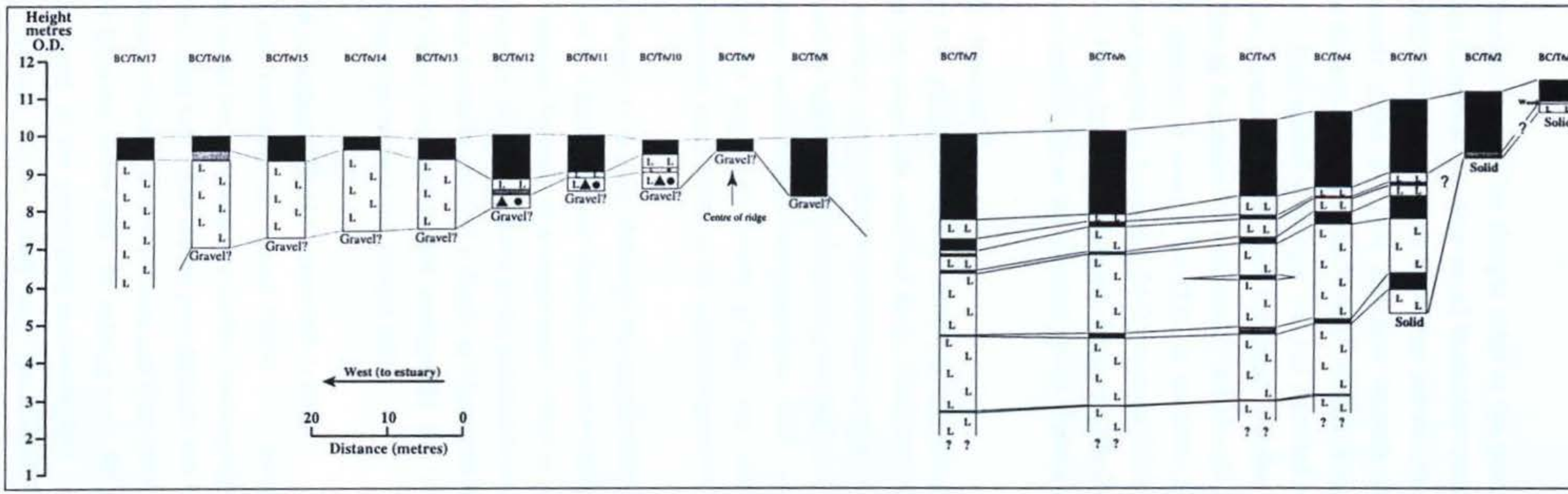


Figure 6.7 Blairs Croft Transect 6: Lithostratigraphical cross-section

The course of this transect crosses the shingle ridge at the point where it descends below the surface peat (Borehole 9). One set of boreholes continues out toward the centre of the Cree valley (8-17) and these show that the shingle associated with the ridge apparently extends under the peat and also beneath the uppermost carse deposits. The spread of the shingle apparently ends between 6 and 7m O.D. (between boreholes 16 and 17). This spread of shingle was not recorded on the landward side of the ridge where at borehole 8 peat, and not carse, overlies the ridge. On the northward transect line of boreholes (9 and 18-25) the shingle ridge is recorded as continuing for some distance at *circa* 9.5m O.D. to borehole 23. At this point the shingle falls in altitude sharply in boreholes 24-25 to *circa* 7.75m O.D. that is at least adjacent to transect 4. Here the carse sediments clearly overlie the buried shingle. No further boreholes were undertaken in the wooded part of Blairs Croft.

6.4.2.5 Blairs Croft: transect 7

The transect (Figure 6.8) presented here is complicated by the presence of a shingle ridge that runs from the valley side south of Blairs Croft and stretches as an arcuate feature through the northern field at Blairs Croft where it appears to disappear beneath the carse and peat surface before terminating in the wooded part of the peat moss (see 6.4.2.4). In this transect, which crosses the ridge, there is no evidence that this feature is spread underneath the uppermost levels of the carse sediments; this differs markedly from the situation *circa* 100m to the north in transect 6.

Evidence for Units 4a and 4b is clear although the height of the uppermost carse and surface peat contact is at a higher altitude than in the other transects (*circa* 10m O.D.). Similarly MHB3 is present but only as a single unit. There is no evidence of a lower buried peat at this location which correlates to the separation between Unit 2 and Unit 1. However, only one borehole reached a depth at which this layer would have been recorded. There is some evidence in the stratigraphy that suggests that the peats extend from the valley edge beneath the shingle ridge.

6.4.2.6 Blairs Croft (transect 3) and Carsewalloch Flow

From the Blairs Croft evidence the buried (Units 1-4) intercalations of peat and estuarine sediments could not be traced any further than approximately 100m from the break of slope at the valley side. The buried peat deposits and underlying fine grained minerogenic sediments recorded at both Palnure and from transect BC/4 are, however, still present further from the valley side. In order to trace the extent of the peat layer and to establish the depth of the underlying sediments four widely spaced boreholes were undertaken between Blairs Croft and Carsewalloch Flow (Figure 6.9).

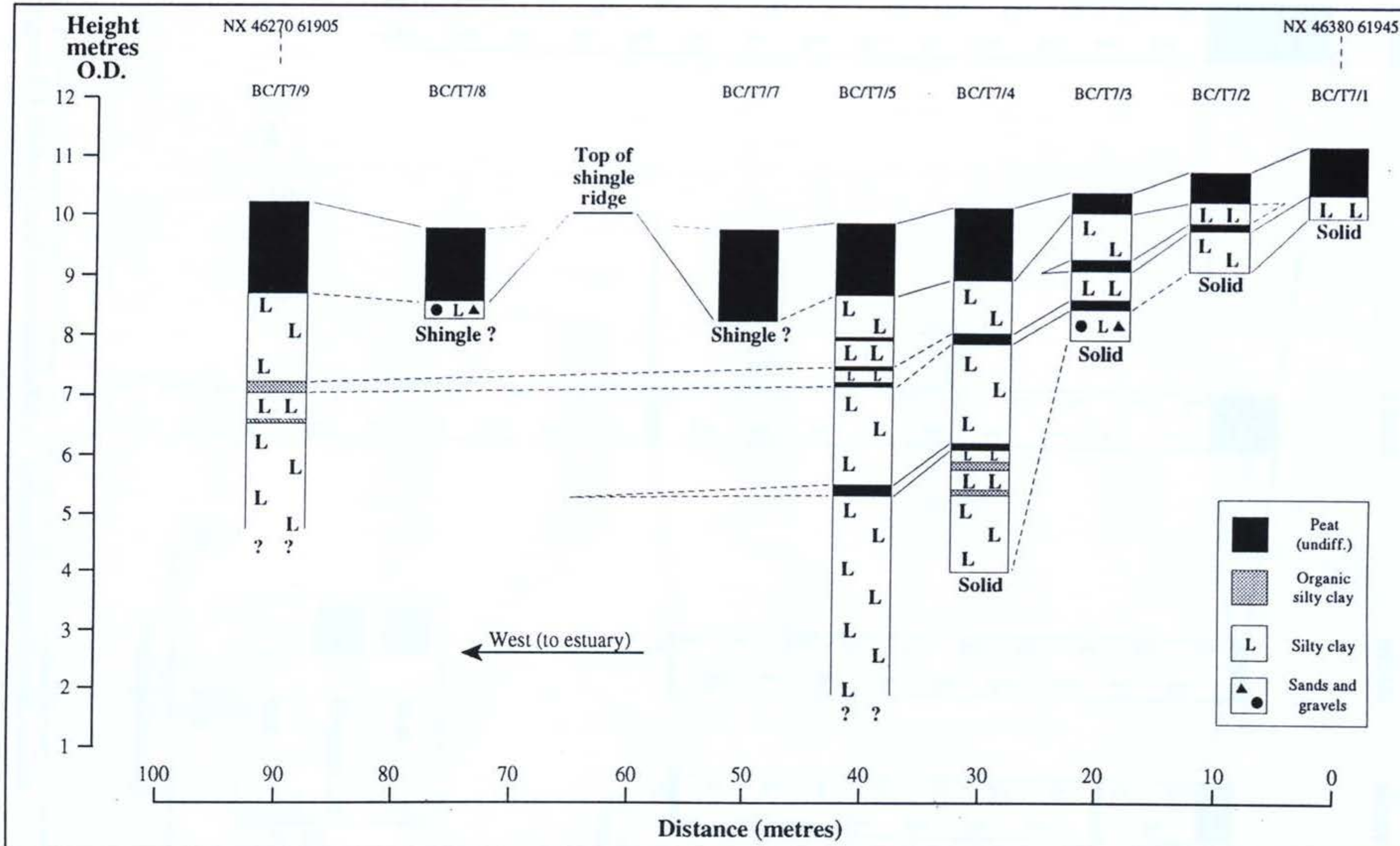


Figure 6.8 Blairs Croft Transect 7: Lithostratigraphic cross-section

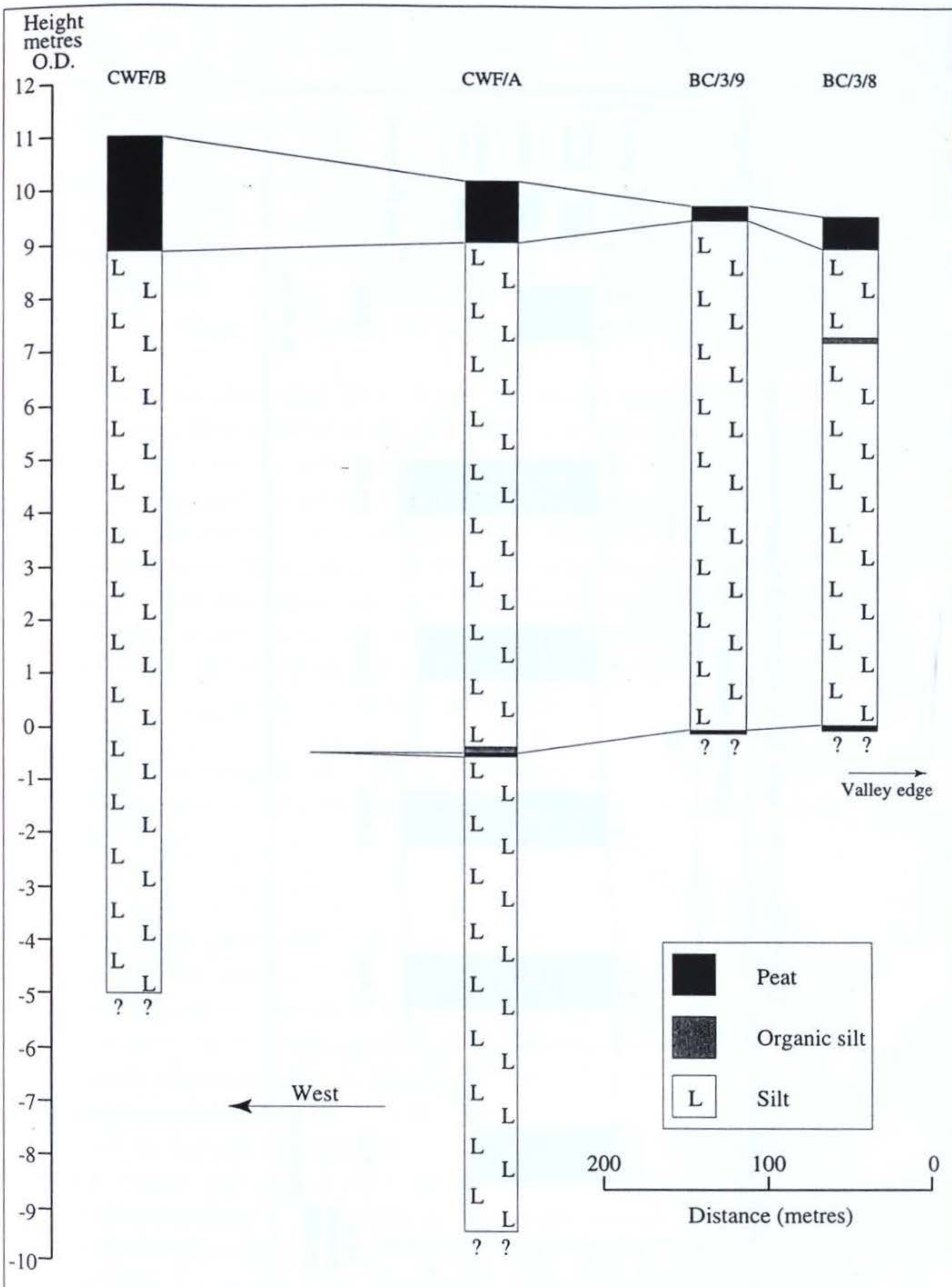


Figure 6.9 Blairs Croft/Carsewalloch Flow: Lithostratigraphical cross-section

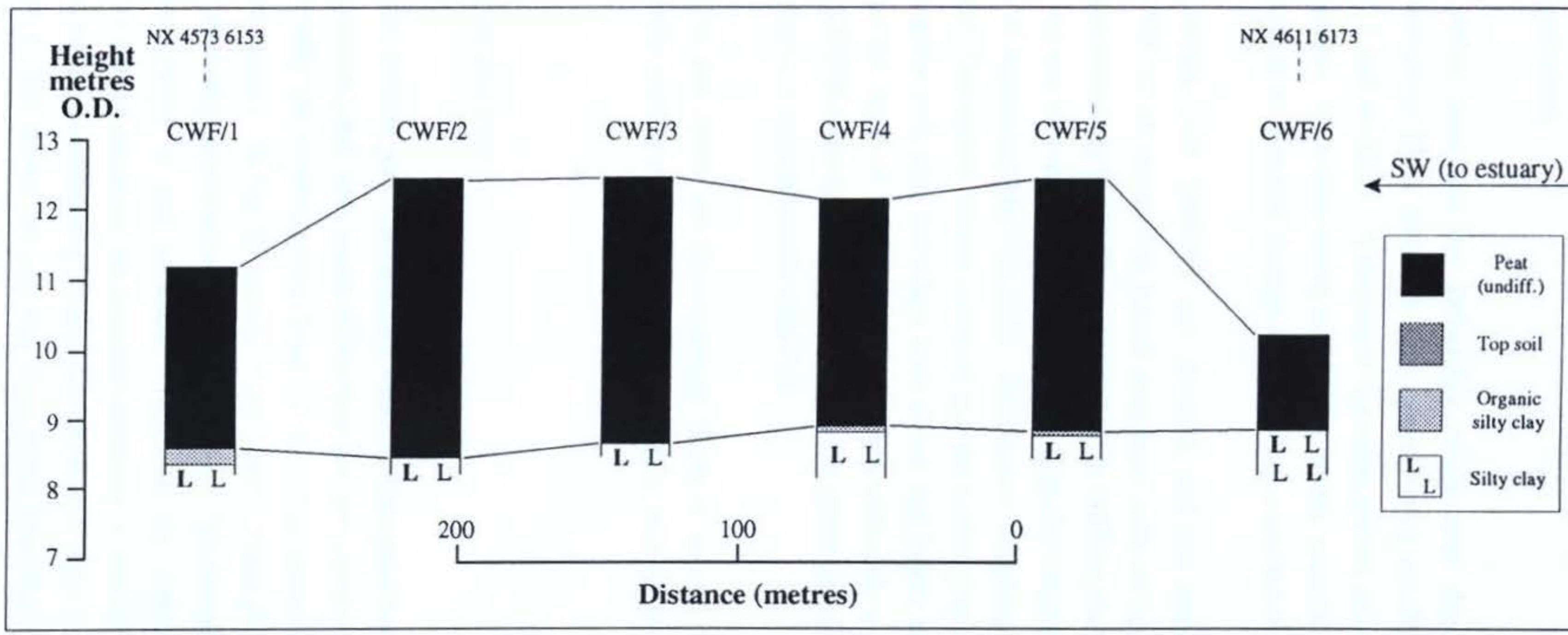


Figure 6.10 Carsewalloch Flow: Lithostratigraphical cross-section

Additional boreholes at Carsewalloch Flow (Figure 6.10) record the junction between surface peat and carse sediments.

The junction of the surface peat and the underlying raised carse deposits in all boreholes across Carsewalloch Flow does not vary greatly with an altitude range between approximately 8 and 9m O.D.. A decline in the carse surface altitude toward the valley centre is apparent. It is also worth noting that on the western side of the ridge at this location there is no apparent shingle spread as was recorded in transect 6.

Two boreholes from Blairs Croft (BC/3/8 and BC/3/9) and one borehole from Carsewalloch Flow (CWF/A) all record the buried peat layer with an upper contact falling steadily from approximately 0m O.D. to -1m O.D.. In CWF/A the buried peat layer was penetrated (but not recovered) and fine-grained silty clay deposits underlie the peat to an altitude of approximately -7m O.D.. Subsequent sampling at this site by a team from the Dutch Geological Survey revealed that the buried peat deposit was only 3cm thick with organic rich silts and clays both above and below over a *circa* 30cm band. In addition the depth of the borehole recovered sediments to a depth of *circa* -9.5m O.D.. In CWF/B there is no buried peat and the minerogenic sediments continued to at least a depth of approximately -6m O.D..

One hundred metres to the south on Carsewalloch Flow a second transect of boreholes records a similar surface peat/carse junction which is level at approximately 8.7m O.D..

6.5 **Castle Clary** (NX 476 579)

6.5.1 Introduction

South of Creetown is the holiday park Castle Clary which is separated from the town by an open area of common land and sports fields that are the carselands. These deposits represent virtually the southernmost limit of the carse sediments on the eastern side of the Cree estuary. In the SE corner of this area is carse (NX 476 579) which has been left (relatively) undisturbed for grazing land. Undisturbed surface peat deposits were not present at this location. Therefore the objective of the lithostratigraphic survey was to establish the possible existence of buried peat layers within the fine grained estuarine sediments. Only two boreholes were undertaken at this site and as a result of this survey no samples were taken from this location for laboratory analysis.

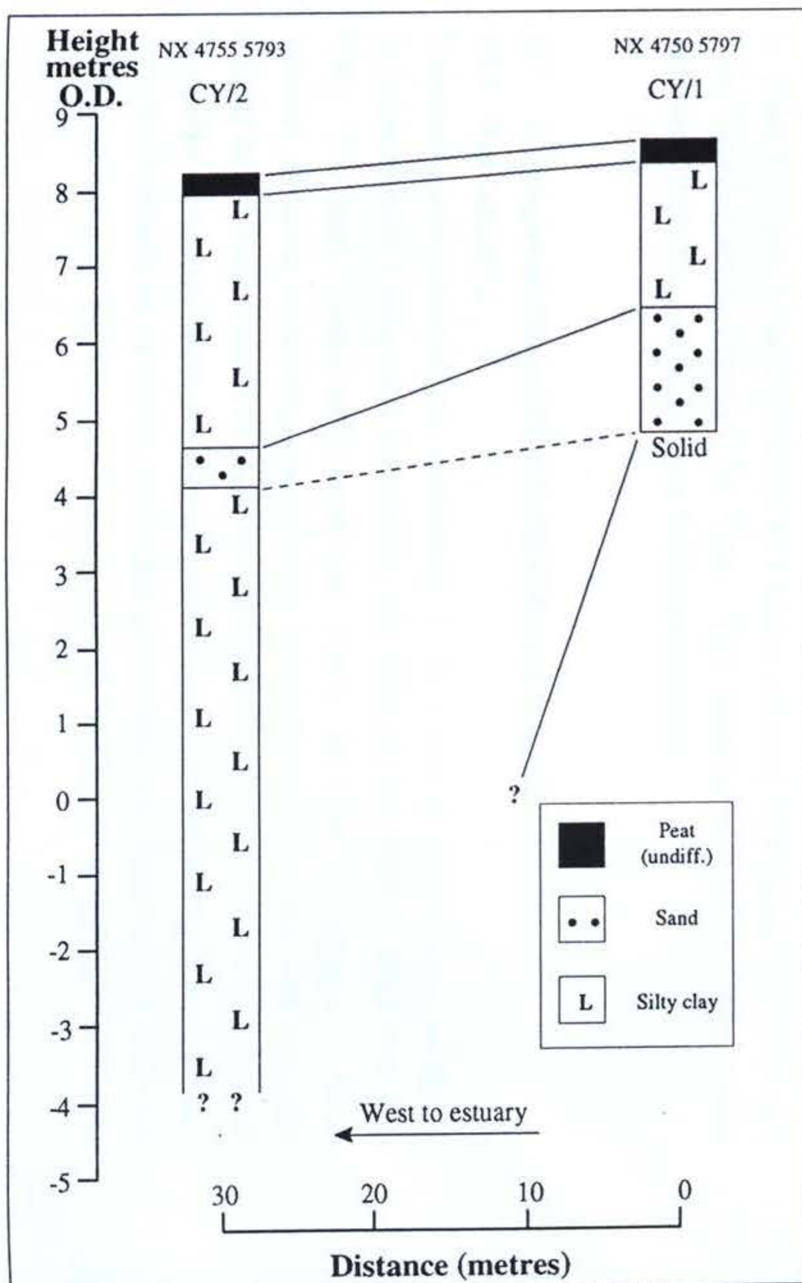


Figure 6.11 C[illegible] Cl[illegible]y: Lithostratigraphical cross section

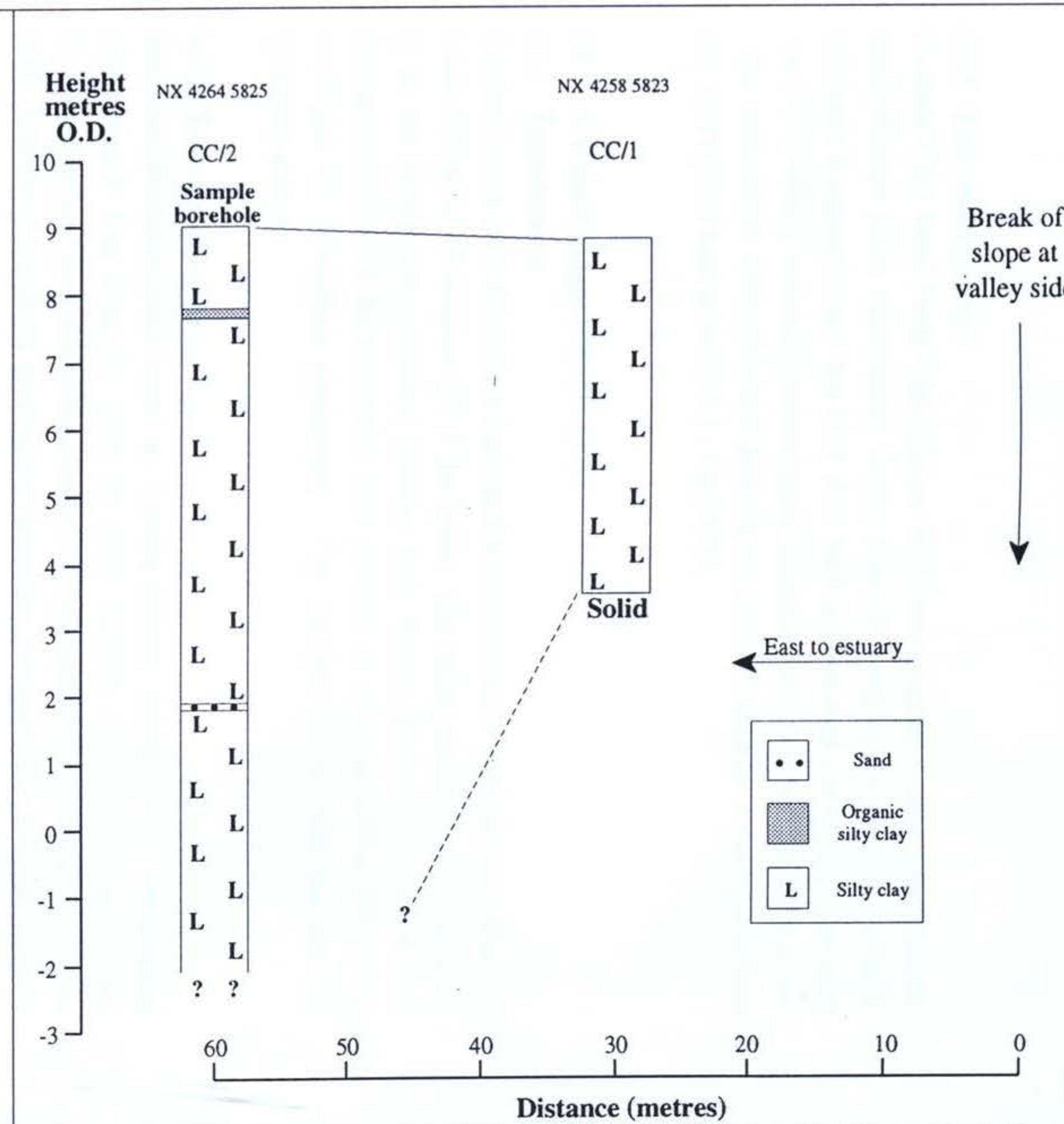


Figure 6.12 Carslae Cottage: Lithostratigraphical cross-section

6.5.2 Lithostratigraphy

Borehole CY/1 from Castle Clary (Figure 6.11) was positioned *circa* 10m from the break of slope at the valley side. A thin layer of peaty topsoil overlies the carse sediments at approximately 8m O.D. that show a downward coarsening from silty clay to silts which eventually become sands at *circa* 6.2m O.D.. At CY/2, 30m closer to the centre of the valley, the carse deposits are recorded down to -3.8m O.D. broken only by a layer of sand between 4.1 - 4.6m O.D..

6.6 Carslae Cottage (NX 427 583)

6.6.1 Introduction

Carslae Cottage (NX 427 583) is built on the carse surface a short distance from the break of slope on the western side of the valley. The valley sides here are not as steep as on the eastern side. Situated between both Borrow Moss (to the south) and Carsegowan Moss (to the north) this area provided an easily accessible location to investigate the sub-surface stratigraphy. One borehole (CC/2) was sampled for laboratory analysis.

6.6.2 Lithostratigraphy

Only two boreholes were cored at Carslae Cottage (Figure 6.12). Positioned approximately 10m from the break of slope borehole CC/1 records silty clays throughout before being able to penetrate no further (probably bedrock) at *circa* 3.5m O.D.. A further 30m toward the centre of the valley borehole CC/2 recorded similarly silty clay throughout interrupted only by a brown coloured silty clay at 7.8m O.D. and a sand layer at approximately 1.9m O.D.. This borehole reached -2m O.D. before equipment limitations prevented any further penetration.

6.7 Carsegowan Moss (NX 425 588)/Moss of Cree (NX 435 600)

6.7.1 Introduction

Lithostratigraphic analysis was undertaken on the extensive peat deposits overlying the carselands at Carsegowan Moss (NX 425 588) and the Moss of Cree (NX 435 600). The peats (mainly unforested) that overlie the carse at Carsegowan Moss continue up to the valley edge immediately below Carsegowan farm (NX 420 587) making this an ideal location to study the sub-surface stratigraphy. Carsegowan Moss is separated from the Moss of Cree by pasture fields and the Bishop Burn that cuts into the carselands on its course to join the River Cree. The Moss of Cree is for the most part covered by Kilsture Forest - a well developed coniferous plantation.

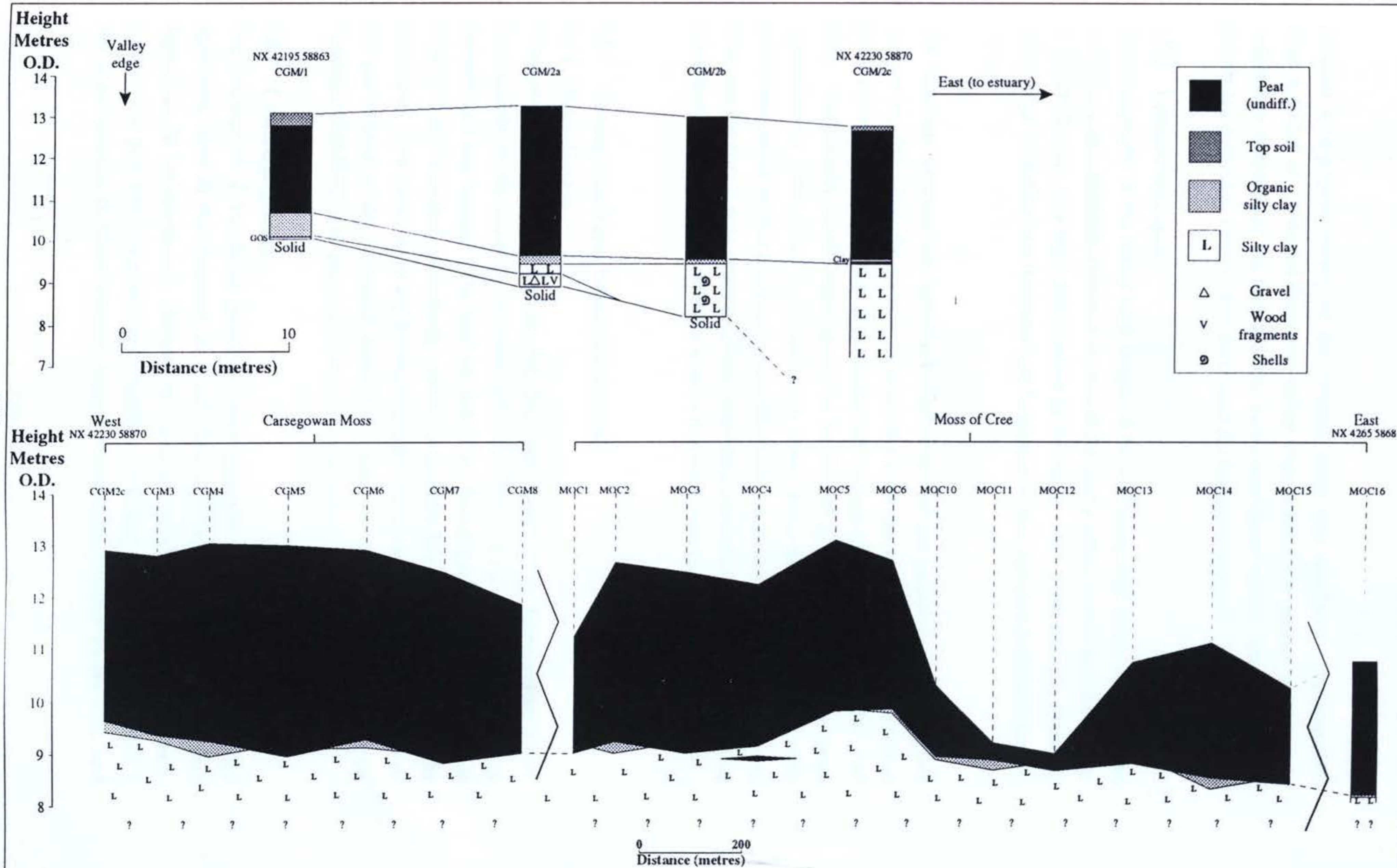


Figure 6.13 Carsegowan Moss/Moss of Cree: Lithostratigraphical cross-section (including detail of the boreholes at the valley edge)

Detailed stratigraphic survey of the forested areas was considered impracticable. Thus a series of boreholes from the valley edge toward the present estuary was undertaken determining the height of the upper carse/peat contact. Five samples of the surface peat/carse contact were recovered for laboratory analysis.

6.7.2 Lithostratigraphy

The stratigraphy at the valley edge (Figure 6.13) of Carsegowan Moss records peats overlying carse sediments (junction at *circa* 9.5m O.D.) which in turn rest on bedrock. In CGM/2b there is a high shell content in the carse. At a short distance from the valley edge (CGM/2c) the thickness and toughness of the silty clay prohibited further coring.

The boundary between the undifferentiated peats and the underlying carse surface appears variable along the transect of boreholes from the valley side at Carsegowan Moss to the edge of the carse at the reclaimed saltings of Polwhilly farm (NX 448 606). The overall trend would appear to be that of a falling carse surface from approximately 9.6m O.D. in CGM/2a to about 8.4m O.D. by MOC/16. The transitional nature of this junction is recorded clearly in a number of these boreholes. Evidence for buried peat deposits is poor with only one borehole (MOC/4) recording a thin peat layer just below the carse surface at *circa* 8.9m O.D..

6.8 Carsegowan Farm Basin (NX 422 588)

6.8.1 Introduction

Carsegowan Farm is situated on the low hills overlooking Carsegowan Moss. Immediately to the north of the farm (NX 422 588) is a basin in which are peat deposits and tree stumps. The rock lip that is the lowest part of the basin (altitude 12.67m O.D.) is located immediately above Carsegowan Moss beneath which are the carselands. The objective of the lithostratigraphic survey was to establish the nature and provenance of the sediments within the basin. As a result of this survey one borehole (CGM/F/7) was sampled for laboratory analysis.

6.8.2 Lithostratigraphy

The transect of 7 boreholes presented from this site (Figure 6.14) records the uppermost layer of the sequence as a soil layer underlain by undifferentiated peat deposits in all but borehole 1. Beneath the peats in the other six boreholes are non-organic blue grey silts, clays and sands similar to the carse sediments - in boreholes 2 and 3 the junction of these deposits range between approximately 10.4m O.D. and

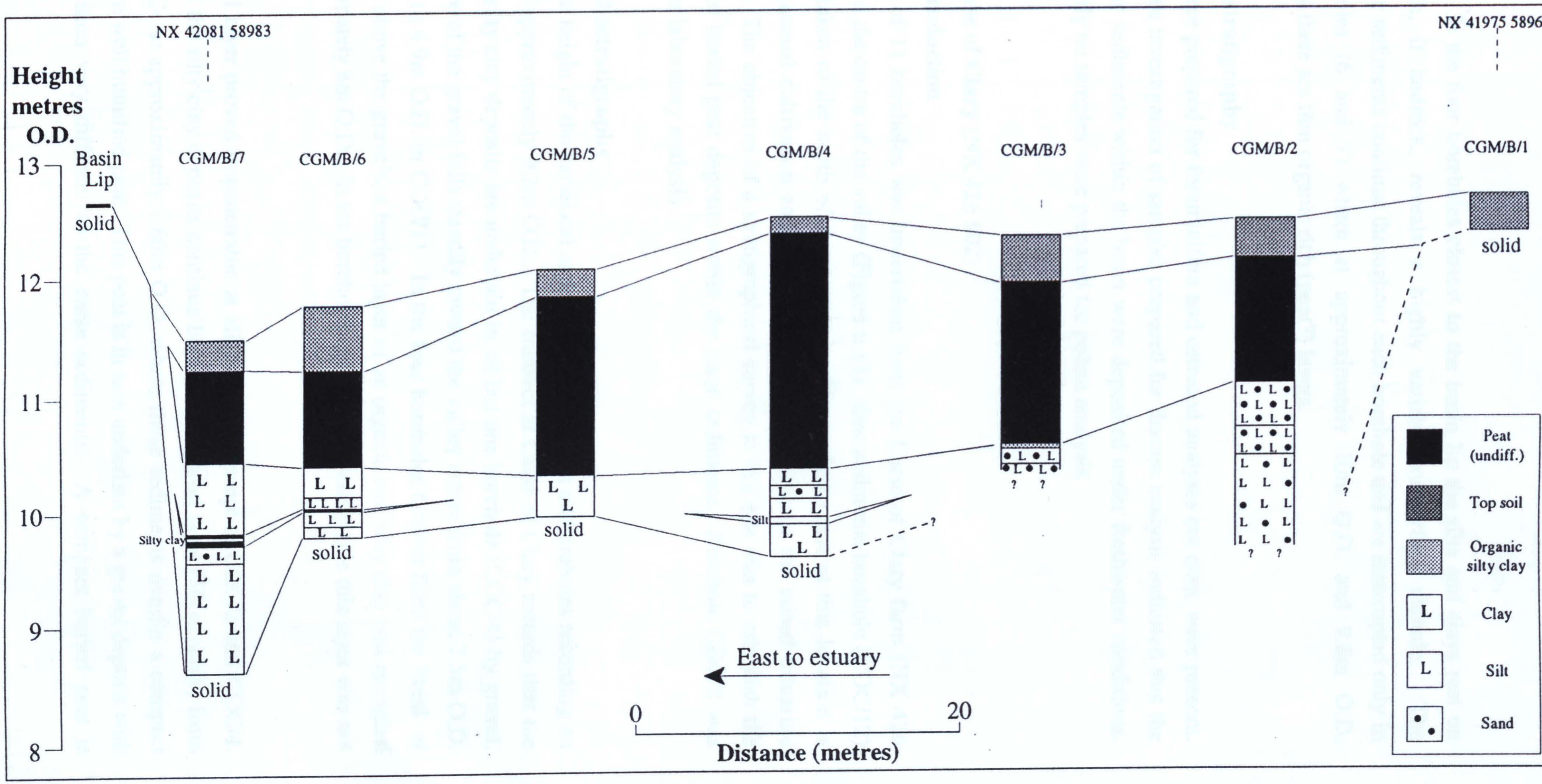


Figure 6.14 Carsegowan Farm Basin: Lithostratigraphical cross-section

11m O.D.. In the four boreholes closest to the basin lip the silts and clays rest on solid which, if bedrock, reveals a highly variable subsurface altitude. The minerogenic sediments continue throughout each borehole and are interrupted only in two boreholes (6 and 7) where at approximately 10m O.D. and 9.8m O.D. respectively there are thin organic rich (peat?) layers.

6.8.3 Biostratigraphy

Samples were prepared for foraminifera and ostracod analyses but none were present. A qualitative investigation of samples prepared for diatom analysis indicated that the minerogenic sediments within the basin were deposited under freshwater conditions. Consequently no samples were prepared for pollen analysis.

6.9 Carse of Clary (NX 426 602)

6.9.1 Introduction

A transect of 11 boreholes was undertaken from the Carse of Clary farm (NX 426 602) toward the centre of the valley (Figure 6.15). One additional borehole (COC/12) was undertaken to the north of this transect. The surface carse at this location is subject to annual cultivation and at no point does peat overlie the raised estuarine sediments. The objective of a stratigraphical survey at this site was to establish the existence of buried peat deposits within the carse sediments. Borehole COC/2 was sampled for laboratory analysis.

6.9.2 Lithostratigraphy

The surface height of the carseland at this site is level with all boreholes recording an altitude of approximately 9.2m O.D.. The transect at Carse of Clary records that the blue/grey silty clay deposits are underlain in all but one borehole (COC/4) by gravel. The surface of the gravel falls steadily toward the valley centre from about 7.5m O.D. in COC/1 to 4.9m O.D. in COC/11. In the four boreholes farthest from the break of slope, and above the gravels, a buried layer of an organic rich silty clay was recorded at approximately 8m O.D.. In the boreholes closer to the valley side this layer was not identified.

The gravel layer proved impenetrable at all boreholes except at COC/2 and COC/4. At COC/2 the silty clay deposits continue beneath the gravel layer (10cm thick) from 6.58m O.D. to approximately 1.80m O.D. where these sediments overlie a compact dark brown well humified peat. This peat is in turn underlain by a gravel deposit with a composition very different to the carse sediments. A compact buried peat is

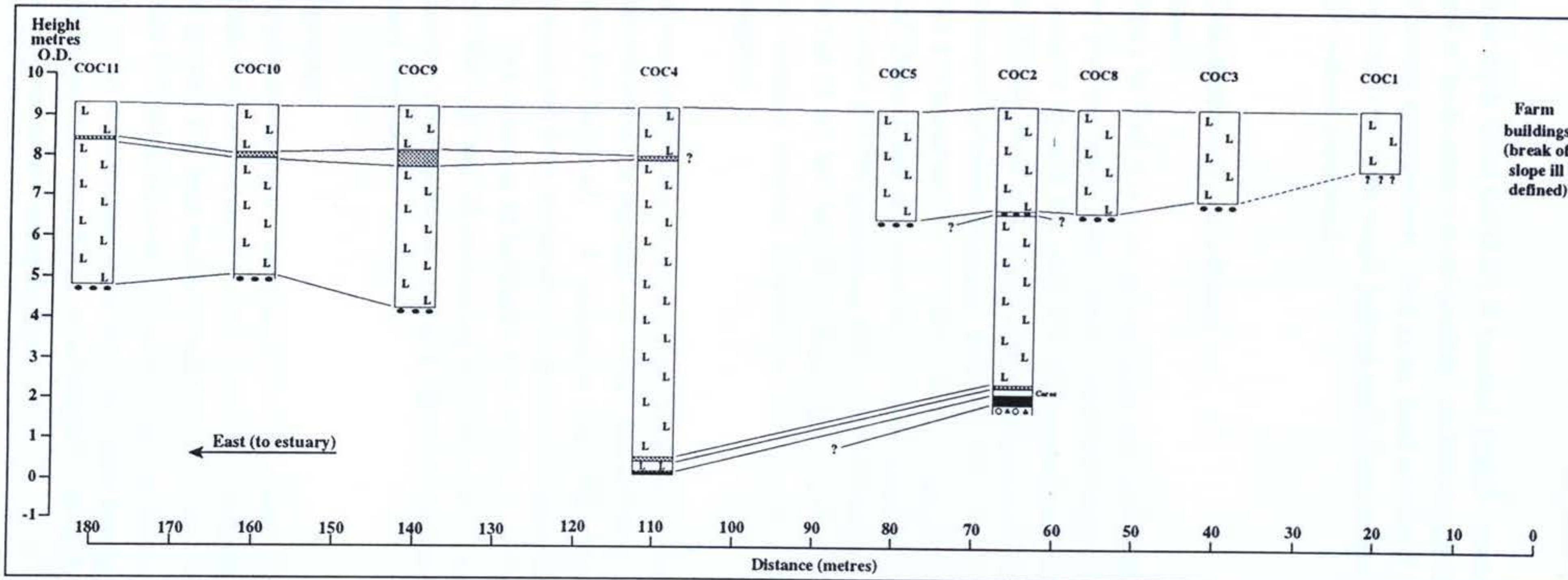


Figure 6.15 Carse of Clary: Lithostratigraphic cross-section

similarly recorded at depth (*circa* 0m O.D.) in borehole COC/4. Further penetration below the peat layer at this location was not possible. No buried peat was recorded in COC/12 which is located approximately 100m to the north of COC/4 and penetrated to an altitude of -1.31m O.D.. This would indicate that the distribution of the buried peat in this location was not widespread.

6.10 Moss of Cree (Baltersan) (NX 430 616)

6.10.1 Introduction

The area of the Moss of Cree that overlies the carse west of Baltersan Farm was investigated in the past by Lewis (1905), Moar (1969) and most recently Jardine (1975). Pollen analysis through the peat and the immediately-underlying carse deposits (NX 430 615) by Moar (*op cit.*) indicates that peat accumulation did not begin at this location until sometime during his zone FV. Jardine (*op cit.*) supported this conclusion with a radiocarbon date of 4,000±100 ^{14}C years BP for a sample of twigs from the basal 25mm of peat at a nearby location (NX 445 614). Since Jardine's research during the 1960's and 70's plantations have grown to overwhelm the Moss of Cree. Baltersan is one of the few locations where coniferous plantations were not grown and it was therefore decided to return to this area for a more detailed stratigraphic investigation.

The stratigraphical investigations were extended to the carselands that lie immediately to the south of Baltersan Farm. In this area any surface peat is absent (probably as a result of clearances for farmland). A distinctive ridge (see Figure 6.1) runs approximately eastwards out from the break of slope and into the unforested part of the Moss of Cree. Two transects of boreholes were undertaken to determine the relationship between the ridge and the surrounding sediments. All stratigraphical and morphological details are presented below (Figure 6.16). One borehole (BAL/3) was sampled for laboratory analysis.

6.10.2 Lithostratigraphy

Transect 1 trends approximately north - south parallel with the break of the slope and records the stratigraphy on either side of a ridge that, from trenching, is comprised mainly of sand and gravel. The three boreholes taken on the south side of the ridge (BF/1 to BF/3) record a simple stratigraphy of silts and clays (ground surface at *circa* 9.8m O.D.) resting on an impenetrable substrate. This layer decreases in altitude away from the ridge feature from *circa* 8m to *circa* 7.4m O.D.. In BF/3 there is some evidence for a peat overlying the impenetrable layer.

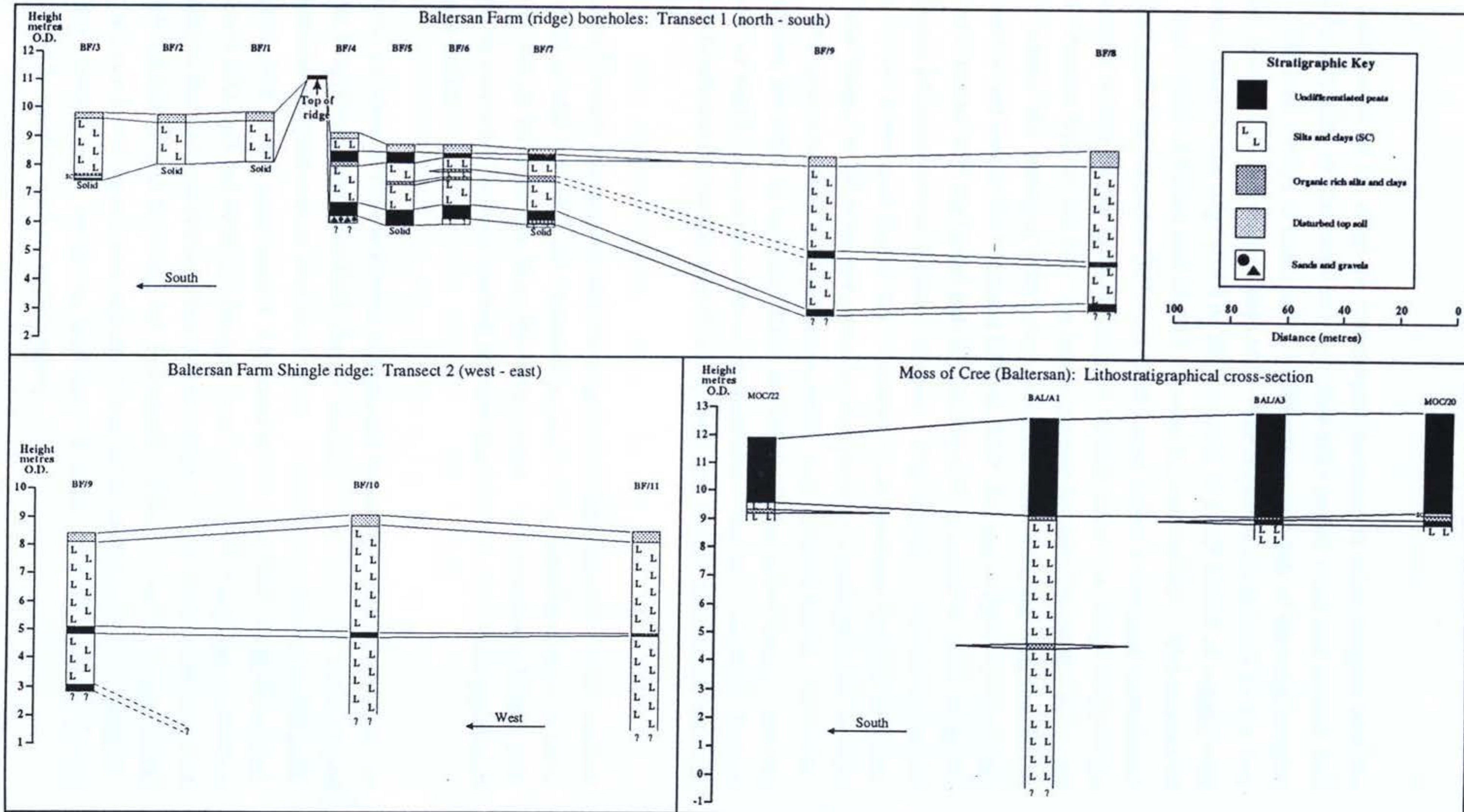


Figure 6.16 Moss of Cree (Baltersan) and Baltersan Farm: Lithostratigraphical cross-sections

Immediately north of the ridge the stratigraphic sequence is more complex with the blue grey silty clay of the carse interdigitating with buried peats and organic rich layers. The land surface is much lower in altitude on this side of the ridge ranging between *circa* 9.2m and *circa* 8.4m O.D.. The uppermost sediments in the four boreholes closest to the ridge (BF/4 to BF/7) consist of a stiff topsoil of organic silty clay. This overlies a buried peat deposit between 8.5 and 8m O.D.. The absence of this intercalation in boreholes BF/9 and BF/8 could reflect a changing depositional environment or may be due to disturbance by farming since it is within 30cm of the surface. Further organic rich silty clay layers (altitude between 7m and 8m O.D.) are present within the blue/grey silty clay sediments that continue underneath the uppermost buried peat in the boreholes BF/5 to BF/7 - but not in BF/4. It is possible that these correlate with the buried peat at *circa* 5m O.D. in boreholes 8 and 9 despite the marked difference in the deposits' altitude. The blue/grey silty clay sediments overlie a lower buried peat deposit that is recorded in all boreholes north of the ridge. In the four closest to the ridge the peat/silty clay junction is between 6.5m to 6.8m O.D.. The peat is underlain by an impenetrable layer at *circa* 6m to 6.2m O.D.. Further from the ridge in boreholes BF/9 and BF/8 a lower buried peat is similarly recorded but with a junction much lower between *circa* 3.2m and 3.4m O.D.. In both of these boreholes the buried peat is compacted and further penetration was not possible.

In transect 2, which runs parallel with the ridge and includes borehole 9 from transect 1, the most notable feature is the continued presence of the buried peat layer at *circa* 5m O.D. which thins further from the valley edge. The lowermost buried peat recorded in borehole 9 was not reached in boreholes 10 an 11 which both penetrated to at least 2m O.D..

In most of the Moss of Cree boreholes at Baltersan the junction between the peat and the carse is approximately 9.5m O.D.. In the one deep borehole (BAL/A/1) the carse sediments were recorded to at least -0.4m O.D. Evidence for a buried peat/organic rich layer close to the carse surface was recorded in a number of the boreholes, particularly BAL/A/3 and MOC/20, lying at *circa* 9m O.D.. Although not recorded in all boreholes there is clear evidence that this buried peat is widespread in this area. In BAL/A/1 the buried peat layer was not recorded but there is some indication in this borehole that a lower organic rich deposit existed in the vicinity at *circa* 4.5m O.D.. This may correlate with the buried peat layer at *circa* 5m O.D. recorded in the boreholes of transect 1 and 2 as detailed above.

6.11 Summary of stratigraphic investigations of the Cree Estuary

The stratigraphic sequence in the valley of the Cree is relatively simple. The carse sediments, which are in places overlain by peat, have a surface that lies between *circa* 7m-9.5m O.D.. At Blairs Croft, in an area approximately delimited by the valley edge and a fossil ridge, there are intercalated peat and carse layers. Correlation between closely spaced transects at this location indicate that there are probably at least four interdigitations of peat and carse. On the other side of the valley at Baltersan Farm a similar situation exists where a larger ridge appears to mark the northernmost limit of carse deposits that are built up to a higher altitude. To the north of the ridge a shorter sequence of intercalating carse and peat layers is recorded. The most notable of these is a buried peat deposit at *circa* 5m O.D.. On the Moss of Cree at Baltersan, and probably seaward of the limit of the ridge, there is evidence of a wedge of silty clay at *circa* 9m O.D. within the surface peats. The stratigraphy records that this wedge eventually merges with the underlying carse sediments forming a continuous sequence of undistinguishable blue/grey silts and clays to the south. Clearly the presence of shingle ridges and buried shingle/gravel layers in an area that is predominantly comprised of silts and clays indicates that there has been variability over time of either sediment supply and/or the energy of the depositional process.

The carse sediments are on occasion underlain by a buried compact peat layer at locations close to the break of slope at the valley side (e.g. Palnure, Carsewalloch Flow/Blairs Croft, Carse of Clary and Baltersan Farm). This peat deposit overlies bedrock when closest to the valley side but farther from the break of slope the buried peat has a generally level surface. Where this leveling out occurs, and in the few boreholes where the compact peat could be penetrated, a lower sequence of fine grained sediments with a junction at *circa* -1m to 1m O.D. was identified. In one borehole (CWF/A) the lower fine grained sediments are recorded to at least -9m O.D.. In other boreholes (e.g. CWF/B, CY/2, CC/2, COC/12 and MOC/A1) across the valley buried peats are not recorded and the carse sediments would appear to be continuous. However, the tapering of the buried compact peat layer at Carsewalloch Flow may mean that the absence of the peats in CWF/B does not rule out the presence of the lower fine grained sediments at this location. Only the similarity of the sediments prevented these two separate deposits from being distinguished in the field.

The complex sequence of buried beaches, peat and gravel layers identified beneath carselands at similar locations elsewhere in Scotland (e.g. the Forth valley - Sissons, 1967) has not been recorded in the present stratigraphical survey of the carselands of the Cree estuary. However, the base of the sediments has never been reached in the centre of the valley and the existence of features lower in the stratigraphical sequence is not ruled out. Only by using more sophisticated field coring equipment that can operate to depths in excess of 20m can the complete soft sedimentary sequence of the Cree estuary be resolved.

Chapter 7 Cree estuary: palaeoenvironmental investigations

7.1 Introduction

In addition to the lithostratigraphical survey the present research has attempted to characterise the deep and apparently homogenous silty clay sediments using palaeoenvironmental techniques. The main objective of this study is to establish the potential of the palaeoenvironmental record stored within these sediments to provide an insight into the evolution of the Cree estuary in response to fluctuations in relative sea-level throughout the Flandrian. The lithologies of each sampled location have been presented and described in Chapter 6 and Appendix E.

On the basis of the results from the lithostratigraphical survey five representative locations (PAL/6, CWF/A, BC/4/2, CC/2 and COC/2) were selected for palaeoenvironmental analysis of the thick intercalating minerogenic/biogenic deposits. In all but one of these boreholes - CC/2 - buried peat beds are recorded. The thickness of sediment sampled was restricted by the coring system to approximately 11m, but, for borehole CWF/A it was possible to recover samples *circa* 19.5m thick using a coring system provided and operated by the Dutch Geological Survey. To determine the depositional environment of the thick minerogenic sediments foraminifera and ostracod analyses were applied at all five locations with supplementary evidence from diatom and particle size analysis at CWF/A. The palaeoenvironmental interpretation of the foraminifera, ostracods and diatom data utilises the biozones identified in Chapter 4. In addition, published investigations of the distribution and ecological requirements of both individual species and also associations of species are also referred to (see Chapter 3).

Pollen analysis was primarily undertaken across organic/minerogenic sedimentary boundaries, prior to radiocarbon dating, in order to assist in determining the possibility of depositional lacunae. Where possible contacts that appeared in the field to be transitional (from minerogenic to organic) were selected to reduce the chances of lacunae - such selection was not always possible for the buried peat/silt sequences. All of the above locations, with the exception of CC/2 where no organic layers were observed, were analysed for pollen. Further samples from carse/surface peat boundaries at CWF/1, CWF/6, CGM/2c, CGM/4, CGM/8, MOC/1, MOC/16 and BAL/A3 were also analysed for their pollen content. An additional palynological investigation of the thick minerogenic sediments at CWF/A was undertaken to

Site/ borehole	Lab. code	C^{14} date (years BP)	Age cal. Years BP (2 sigma) (* denotes max/min values)	Altitude (metres OD)	Altitude error (metres)	National Grid Ref. (NX) (8 or 10 figs.)	Material	Environment	Tendency	C^{14} Procedure (* denotes extended counting time)
PAL/6	Beta-105932	6100±70	7175-6780	8.69 to 8.66	±0.47	44905 63630	Peat	Regressive contact	Negative	Standard
PAL/6	Beta-96326	8190±80	9380-8960	-1.13 to -1.10	±0.47 + 0.03	44905 63630	Peat	Transgressive contact	Positive	Standard
PAL/6	Beta-96327	8310±100	9475-8985	-1.15 to -1.13	±0.47	44905 63630	Peat	Regressive contact	Negative	Standard
BC/4/2	Beta-96324	8400±80	9495-9120	0.88 to 0.85	±0.47 + 0.36	46365 62228	Peat	Transgressive contact	Positive	Standard
BC/4/2	Beta-100914	7820±80	8935-8400*	3.49 to 3.45	±0.47 + 0.03	46365 62228	Peat	Trans. and regressive	Pos/Neg	Standard
BC/4/2	Beta-100915	7830±110	8965-8375	5.78 to 5.81	±0.47	46365 62228	Peat	Regressive contact	Negative	Standard
BC/4/2	Beta-100916	7240±90	8155-7890	5.86 to 5.89	±0.47 + 0.08	46365 62228	Peat	Transgressive contact	Positive	Standard*
BC/4/2	Beta-100917	7510±310	8995-7660	6.93 to 6.96	±0.47	46365 62228	Peat	Regressive contact	Negative	Standard*
BC/4/2	Beta-100918	7210±120	8175-7735	7.06 to 7.09	±0.47 + 0.09	46365 62228	Peat	Transgressive contact	Positive	Standard*
BC/4/2	Beta-100919	6800±130	7890-7395	7.16 to 7.19	±0.47	46365 62228	Peat	Regressive contact	Negative	Standard*
CWF/1	Beta-83748	3810±70	4410-3975	8.59 to 8.61	±0.47	4573 6152	Peat	Regressive contact	Negative	Standard
CWF/6	Beta-83749	4010±80	4815-4250*	8.94 to 8.96	±0.47	4611 6172	Peat	Regressive contact	Negative	Standard
CWF/A	Beta-92209	9680±50	Not available	-9.37 to -9.32	Not applicable	46095 61805	Shell	Inter-/sub-tidal seds.	None	AMS
CWF/A	Beta-96325	8580±80	9820-9430*	-0.57 to -0.54	±0.47 + 0.02	46095 61805	Peat	Trans. and regressive	Pos/Neg	Standard
CGM/2c	Beta-84189	3050±60	3375-3070	9.60 to 9.62	±0.47	42230 58870	Peat	Regressive contact	Negative	Standard
CGM/4	Beta-83746	4050±90	4830-4275	9.23 to 9.25	±0.47	4239 5890	Peat	Regressive contact	Negative	Standard
CGM/8	Beta-83747	3680±60	4155-3845	8.97 to 9.00	±0.47	4302 5898	Peat	Regressive contact	Negative	Standard
MOC/1	Beta-83750	4050±50	4810-4410*	8.98 to 9.00	±0.47	4327 5987	Peat	Regressive contact	Negative	Standard
MOC/16	Beta-83751	4330±80	5235-4655*	8.21 to 8.23	±0.47	4974 6063	Peat	Regressive contact	Negative	Standard
COC/2	Beta-96323	8600±90	9850-9430	2.16 to 2.13	±0.47 + 0.16	42713 60248	Peat	Transgressive contact	Positive	Standard
BAL/A3	Beta-96320	5030±110	5985-5585	9.16 to 9.19	±0.47	4296 6176	Peat	Regressive contact	Negative	Standard*
BAL/A3	Beta-96321	5770±90	6775-6395	9.09 to 9.06	±0.47 + 0.16	4296 6176	Peat	Transgressive contact	Positive	Standard
BAL/A3	Beta-96322	6470±80	7470-7205	8.86 to 8.89	±0.47	4296 6176	Peat	Regressive contact	Negative	Standard

Table 7.1 Cree estuary: Radiocarbon dated relative sea-level index point details

Site/borehole	Lab. code	^{14}C date (years BP)	Altitude (metres O.D.)	National Grid Ref. (NX)	Material	^{14}C Procedure
Hollanbank	GU-374	2027±108	5.24	482 555	Shell	Standard
Crook of Baldoon	I-5068	2290±95	5.15	440 530	Shell	Standard
Moss of Cree	I-5513	4000±100	8.35	445 614	Wood	Standard
Muirfad	SRR-26	4746±50	7.92	453 620	Wood	Standard
Newton Stewart	Q-639	6159±120	4.25	416 640	Wood	Standard
Palnure borehole	Birm-189	6240±240	6.38	450 636	Wood	Standard
Palnure borehole	Birm-415	6540±120	6.38	450 636	Peat	Standard
Carseminnoch	I-5514	6325±120	4.30	443 626	Wood	Standard
Little Park	Birm-219	7450±200	6.34	450 657	Wood	Standard
Bargaly borehole	Birm-188	7960±350	6.30	596 589	Wood	Standard

Table 7.2 Radiocarbon dates for the Cree estuary of Jardine (1975)

determine the potential of this record for establishing a history of vegetational change.

7.2 Chronology

The time-frame of the sampled cores is provided by three distinct sources. The main chronological framework is based on the radiocarbon dates detailed in Table 7.1. As a consequence of the following investigations described below the majority of these dates are utilised as relative sea-level index points (see Chapter 8) and the detail of the information provided for each date reflects this application. These have been included as coventional radiocarbon ages (^{14}C years BP) in all microfossil diagrams.

Secondly, palynological investigations have been applied in borehole CWF/A, and of particular use in providing a timescale for deposition is the *Alnus* rise - a phenomenon well documented around the British Isles (Smith, 1984). The identification of the *Alnus* (Alder) rise at the nearby coastal location of Brighouse Bay (Chapter 7) has been radiocarbon dated (conventional age 7,660±60 ^{14}C years BP). It should not be assumed that the *Alnus* rise occurred synchronously at all locations for this phenomenon is known to have been diachronous around the British Isles (e.g. Birks, 1989). It is hoped, however, that the close vicinity of the two locations and their coastal situation will allow for a general correlation of the timing of the *Alnus* rise to be made. In the minerogenic sediments where there is little or no organic content the presence (or absence) of an *Alnus* rise has been used as an approximate chronological marker.

Finally, Jardine (1975) detailed a number of radiocarbon dates from the carse/surface peat boundary for this region. Where these dates are near to a sample site and where no radiocarbon date has been undertaken on the sampled core they have been included (see Table 7.2).

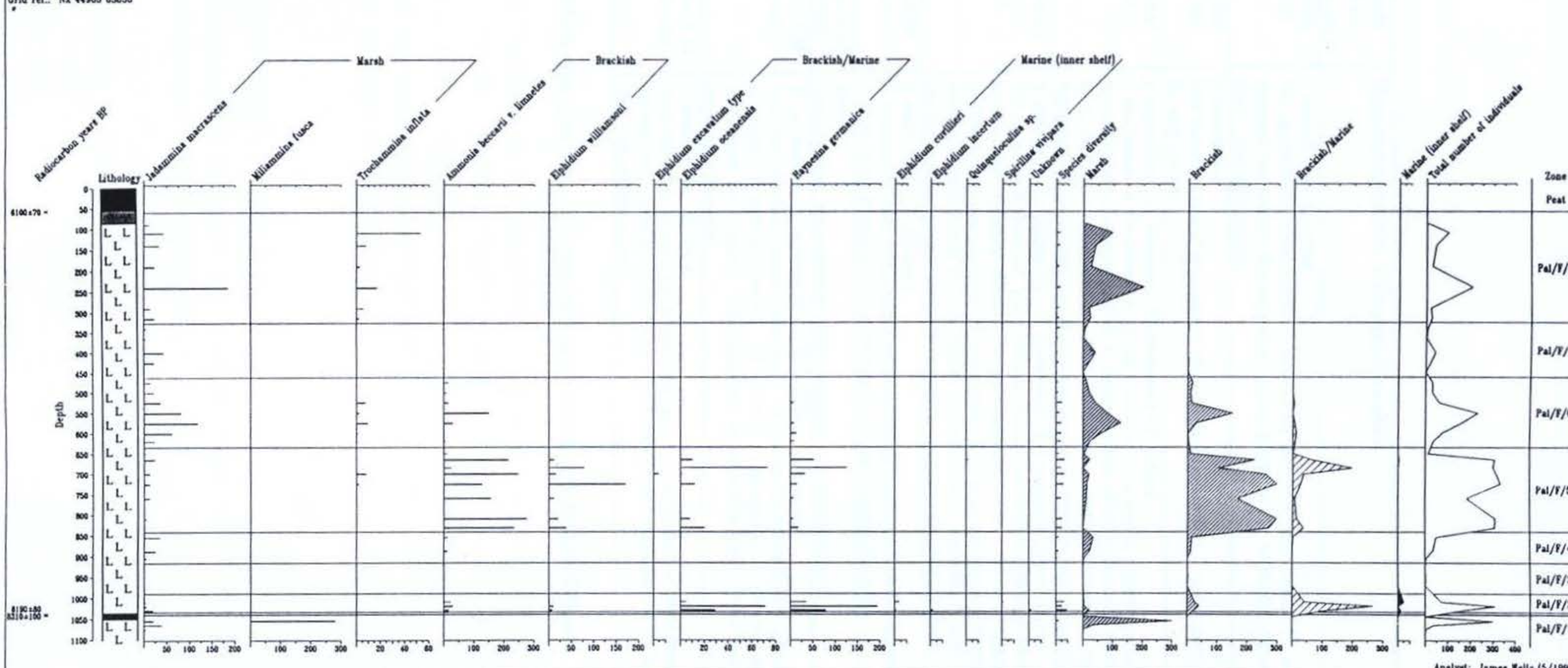
7.3 Palnure

7.3.1 PAL/6: Foraminifera analysis (Figure 7.1; Table 7.3)

Foraminifera analysis on the sampled core PAL/6 taken from Palnure (see section 6.3.2) has allowed the identification of eight distinctive phases (Figure 7.1). A summary of each phase and the main foraminifera associations are presented in Table 7.3. Throughout the sequence foraminifera abundance was highly variable with counts of over 300 tests possible in some levels but in general less than this number

Figure 7.1 Palnure: Foraminifera

Borehole: PAL/8
Height: 9.28m O.D.
Grid ref.: NX 44905 63830



PAL/6 Foram. Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of foraminifera phase
PAL/F/8	**8.66-5.99** 60-327	***J. macrescens - T. inflata*** The agglutinating foraminifera *J. macrescens* and to a lesser degree *T. inflata* dominate this phase. The only other species present is the occasional test of *M. fusca* - also agglutinating.
PAL/F/7	**5.99-4.64** 327-462	***J. macrescens*** Low concentrations of foraminifera characterise the phase with *J. macrescens* being the main species.
PAL/F/6	**4.64-2.91** 462-635	***J. macrescens - A. limnetes - H. germanica - T. Inflata*** *J. macrescens* is the dominant species which rises to a peak in numbers mid-phase coinciding with a marked peak in *A. limnetes* values which is otherwise present in all levels in low concentrations. Similarly *T. inflata* numbers are low but increase mid-phase. *H. germanica* is present in low numbers for the first part of the phase.
PAL/F/5	**2.91-0.84** 635-842	***A. limnetes - E. williamsoni - H. germanica - E. oceanensis - J macrescens*** The dominant *A. limnetes* values fluctuate throughout the phase although the broad trend is one of falling numbers in the uppermost levels. All three species *E. williamsoni*, *H. germanica* and *E. oceanensis* are common and appear to increase in numbers synchronously at *circa* 680cm. *J. macrescens* is recorded in most levels and increases in numbers gradually toward the uppermost levels of the phase.
PAL/F/4	**0.84-0.09** 842-917	***J. macrescens - A. limnetes*** *J. macrescens* is the main species present although it occurs in low concentrations. *A. limnetes* is recorded in two of the three levels that comprise the phase.
PAL/F/3	**0.09 to -0.64** 917-990	**Barren** The occasional test is recorded in the phase which is otherwise barren.
PAL/F/2	**-0.64 to -1.09** 990-1035	***H. germanica - E. oceanensis - J. macrescens - A. limnetes*** This zone overlies a buried peat layer. *H. germanica* numbers are high and *E. oceanensis* is well represented. In addition *J. macrescens*, *A. limnetes* and *E. williamsoni* are common. The occasional test of marine (inner shelf) species is recorded in the phase.
PAL/F/1	**-1.14 to -1.74** 1040-1100	***J. macrescens - M. fusca*** This phase lies beneath the buried peat layer. *J. macrescens* concentrations are variable but is present in most levels. One level records a single peak of *M. fusca* at very high concentrations.

Table 7.3 Main characteristics of foraminifera phases in core PAL/6, Palnure.

was achieved. Twelve species have been identified. The buried peat and surface peat deposits were not sampled for foraminifera.

PAL/F/1 -1.74 to -1.14m O.D. [Depth: 1100-1040cm]

This lowermost phase underlies the buried peat deposits. *Jadammina macrescens* is present in the levels sampled immediately below the buried peat. In one level *Miliammina fusca* is present in large numbers. Both of these agglutinating species and the absence of calcareous species indicate that the environment was probably on the lower saltings terrace. This evidence suggests that it is unlikely that the progression to terrestrial peat deposition would have been interrupted for any substantial amount of time.

PAL/F/2 -1.09 to -0.64m O.D. [Depth: 1035-990cm]

Overlying the buried peat this phase differs markedly from the previous one. Although *J. macrescens* is still present the dominant species is *Haynesina germanica* with *Elphidium oceanensis*, *Ammonia limnetes* and *Elphidium williamsoni* also recorded. In addition a number of marine (inner shelf) species are present but are undoubtedly allochthonous. Ordinarily the association of these species would indicate a very brackish, intertidal, low marsh with *Spartina* (Murray, 1991). However, the presence of *E. oceanensis* and the paucity of *J. macrescens* may suggest that vegetation was limited and the environment would have been that of an estuarine intertidal mudflat. The abundance of all species falls in the uppermost level of the phase - the reasons for this are unknown.

PAL/F/3 -0.64 to 0.09m O.D. [Depth: 990-917cm]

This phase is essentially barren of foraminifera tests. Whether this is due to altitude above mean sea level or poor preservation is unclear. Modern analogues from the higher saltings surface (Chapter 4) in this region have, however, shown that foraminifera are not apparently present in this environment. The absence of foraminifera here may indicate that the environment here was one of a higher saltings terrace.

PAL/F/4 0.09 to 0.84m O.D. [Depth: 917-842cm]

A return in low numbers of *J. macrescens* and to a lesser degree *A. limnetes* indicate a lower saltings terrace depositional environment.

PAL/F/5 0.84 to 2.91m O.D. [Depth: 842-635cm]

This phase is dominated mainly by *A. limnetes* following a sharp increase in numbers in the lowermost level. Other species including *E. williamsoni*, *E. oceanensis* and *H. germanica* are all common throughout but each of these increase to a synchronous peak in the uppermost levels. Of the agglutinating species *J. macrescens* continues to be represented frequently albeit in low numbers; *Trochammina inflata* and *M. fusca* both record a presence. The broad environment maintained throughout this phase is that of a well protected, brackish, intertidal mudflat and, with the possible exception of PAL/F/2, probably represents the part of the sequence lowest in the tidal regime. This is certainly the case for the uppermost half of the zone where *H. germanica* and *E. oceanensis* both peak, all agglutinating forms are absent and marine (inner shelf) species record a presence. At no point, however, does the assemblage indicate that this location was closer to the open sea than in previous levels. The upper level records a decline in all species and is only tentatively included in Pal/F/5.

PAL/F/6 2.91 to 4.64m O.D. [Depth: 635-462cm]

Jadammina macrescens is represented in all levels of the zone peaking mid-phase. This coincides with the increased presence of *T. inflata* and a distinctive peak in numbers of *A. limnetes*. *Haynesina germanica* is present in low numbers in the lower half of the phase. This association of species is broadly indicative of a brackish/marine lower saltings terrace environment.

PAL/F/7 4.64 to 5.99m O.D. [Depth: 462-327cm]

Apart from the occasional presence of *A. limnetes* and *M. fusca* only *J. macrescens* is recorded regularly in low numbers. The indicative environment, similar to the previous phase, is that of a brackish lower saltings terrace. Differences in faunal assemblage between this phase and PAL/F/6 possibly reflects an increased altitude above mean tide level or alternatively an increased distance from the open marine waters of Wigtown Bay. The relatively low abundance of individuals in this phase may be indicative of a fluctuating environment between the lower and higher saltings terraces.

PAL/F/8 5.99 to 8.66m O.D. [Depth: 327-60cm]

The final phase of this sequence which lies immediately below a peat horizon is dominated by *J. macrescens*. In contrast to the previous phase, however, *T. inflata* is also well represented throughout. *M. fusca* records a presence occasionally. The assemblage, as with the previous two phases, is indicative of the lower saltings terrace facies. A progressive reduction in numbers toward the top of this phase probably indicates that the transition to terrestrial peat formation was gradual.

7.3.2 PAL/6: Ostracod analysis (Figure 7.2; Table 7.4)

Ostracod analysis on the sampled core PAL/6 taken from Palnure has allowed the identification of five phases (Figure 7.2). Details of each phase and the main ostracod associations are summarised in Table 7.4. Throughout the sequence low numbers of ostracods are present and only in one level were in excess of 300 valves recorded. Five species have been identified. Peat deposits were not sampled for ostracods.

PAL/O/1 -1.14 to -1.74m O.D. [Depth: 1040-1100cm]

This lowermost phase is almost devoid of ostracods. In two levels ostracods are present but could not be identified with any certainty. The species are thought to be freshwater ones that could have been either derived or were living in pools on a salt-marsh surface. Brackish and marine ostracod species are absent. This phase is overlain by a buried peat deposit with which there is no indication of an hiatus.

PAL/O/2 -0.64 to -1.09m O.D. [Depth: 990-1035cm]

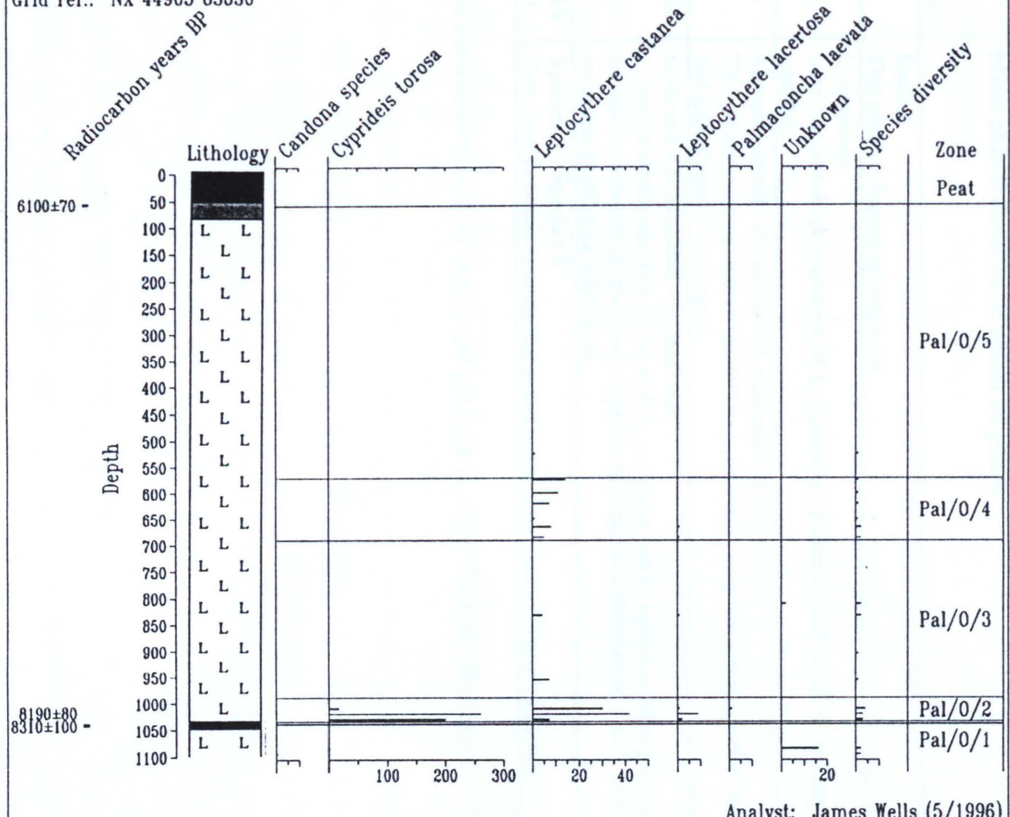
Immediately above the buried peat deposits brackish water ostracods are present in relative abundance. The euryhaline *Cyprideis torosa* dominates the assemblage with *Leptocythere castanea* and *Leptocythere lacertosa* also present. In one level *Palmoconcha laevata* is also recorded. This association of species indicates a well protected estuarine environment probably on a low intertidal mudflat at a distance from open marine conditions. That this association starts almost immediately above the peat layer without a distinctive gradation from a high marsh fauna to low intertidal faunas may indicate an erosive contact. Alternatively inundation of the peat deposits may have been so rapid as to not have recorded any intermediate stages.

PAL/O/3 2.34 to -0.64m O.D. [Depth: 692-990cm]

This phase is almost barren of ostracods. In only four levels were ostracods recorded and in which no species reached 10 valves. Those species present are *C. torosa*, *L. castanea* and *L. lacertosa*. The assemblage reveals little about the environment of deposition as the low numbers can not categorically be classed as being *in situ*.

Figure 7.2 Palnure: Ostracods

Borehole: PAL/6
Height: 9.26m O.D.
Grid ref.: NX 44905 63630



PAL/6 Ostracod Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of ostracod phase
PAL/O/5	**3.54-8.66** 60-572	**Barren** This phase is barren of ostracods.
PAL/O/4	**2.34-3.54** 572-692	***L. castanea*** Low but consistant numbers of *L. castanea*. Probably indicative of an intertidal mudflat.
PAL/O/3	**-0.64-2.34** 692-990	**Almost barren - (*C. torosa* - *L. castanea* - *L. lacertosa*)** This phase is almost barren of ostracods with only very low numbers of *C. torosa*, and *Leptocythere* sp. present.
PAL/O/2	**-1.09 to -0.64** 990-1035	***C. torosa* - *L. castanea* - *L. lacertosa*** *C. torosa* dominates this phase with *L. castanea* and *L. lacertosa* also present. *P. laevata* is recorded in one level. Species association indicative of a well protected estuarine mudflat or tidal creek.
PAL/O/1	**-1.74 to -1.14** 1040-1100	**Species 1 - Species 2** Two levels contain species that could not be identified. Otherwise barren.

Table 7.4 Main characteristics of ostracod phases in core PAL/6, Palnure.

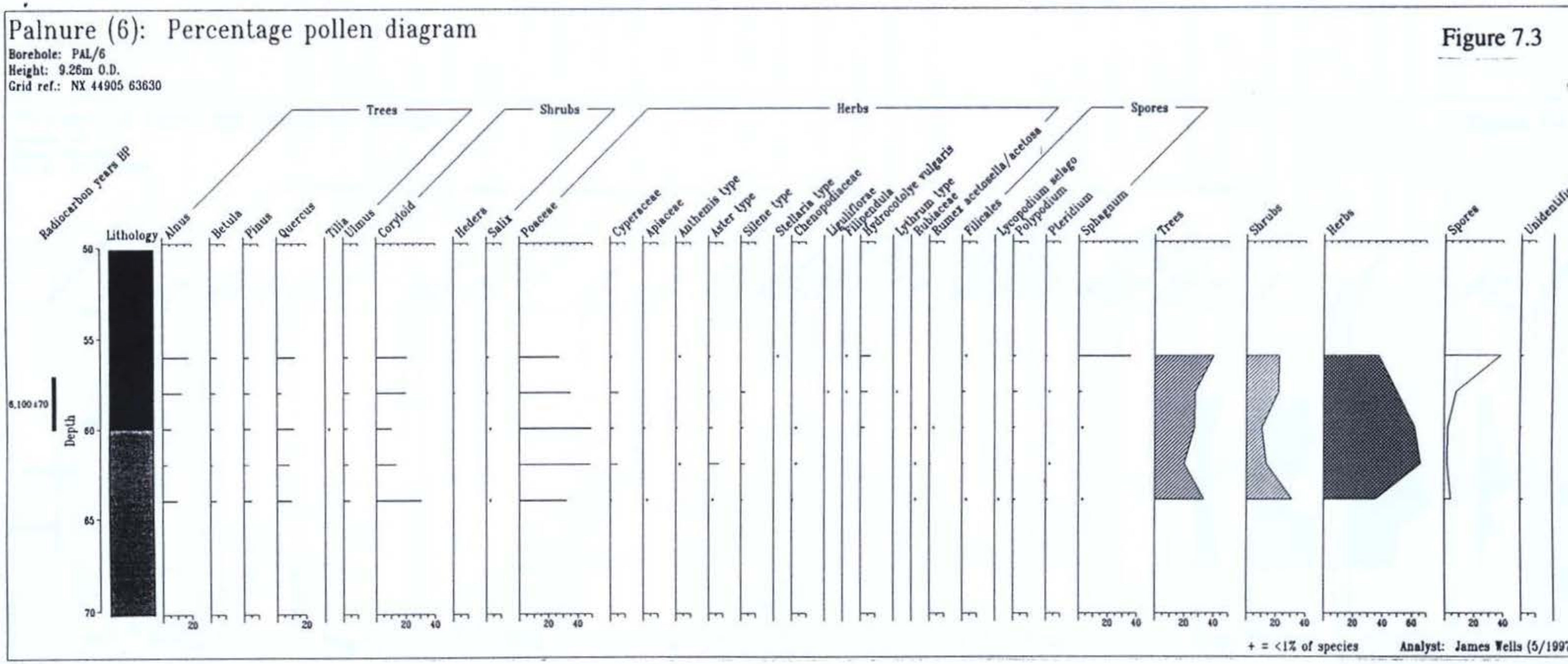
PAL/O/4 3.54 to 2.34m O.D. [Depth: 572-692cm]
Leptocythere castanea is present in consistent, if low, numbers throughout this phase. As with the previous phase it is difficult to establish whether the ostracod present are autochthonous or allochthonous. If these individuals are *in situ* then the indicated environment remains as a well protected intertidal mud-flat or marsh.

PAL/O/5 8.66 to 3.54m O.D. [Depth: 60-572cm]
Apart from one record of *L. castanea* from one level this phase is barren of ostracod which could reflect either a saltmarsh environment or alternatively poor preservation. Peat overlies the sediments that comprise this phase.

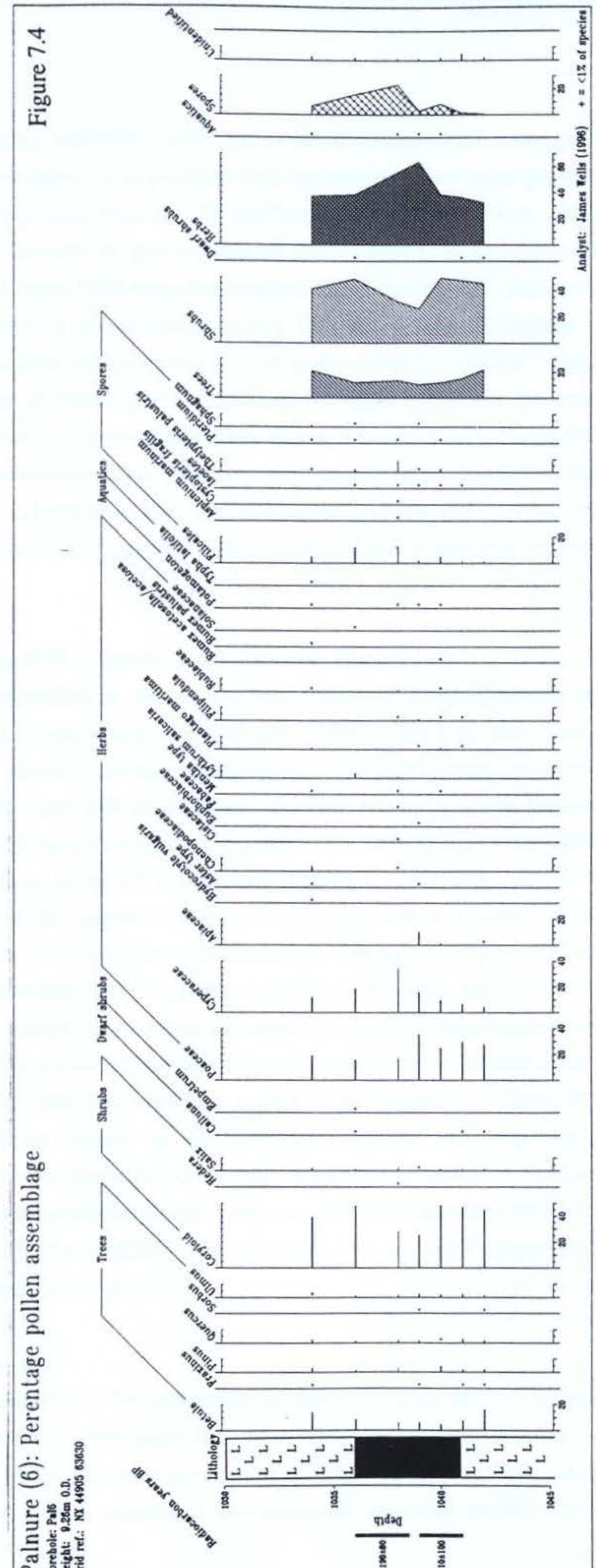
Apart from one zone (PAL/O/2) the presence of ostracods in this core is poor. It is uncertain whether this is a result of poor preservation or that the environment of deposition was not conducive to the existence and/or survival of ostracods.

7.3.3 PAL/6: Pollen analysis (Figures 7.3 and 7.4)
Sediment was sampled from the peat/estuarine sediment boundaries for pollen analysis at this location. Jardine (1975) acquired two radiocarbon dates at Palnure from the surface peat/carse contact and recorded a weighted mean date of 6,480±107 ^{14}C years BP. The difference in altitude between this dated contact and the altitude recorded from the same general location has necessitated the replication of a radiocarbon date in this research (Figure 7.3). The previously undated peat deposits sandwiched between the carse and buried estuarine sediments provided an ideal opportunity for establishing the timing of a probable relative sea-level fluctuation (Figure 7.4). The results of the pollen analysis have not been zoned given the relative homogeneity of the pollen record.

Altitude: 8.56-8.76m O.D. [Depth: 50-70cm] (Figure 7.3)
There is little variability in the arboreal pollen spectra across the sediment boundary. The main arboreal taxa are *Alnus* (<20%), *Quercus* (<20%) and Coryloid (<35%). *Betula*, *Pinus* and *Ulmus* are also well represented with pollen values of *circa* 5% throughout. Poaceae pollen, however, are the main taxa (>25%) with values rising to a maximum of *circa* 45% TLP close to the sediment boundary. Herb diversity is high with *Aster* type, *Silene* type and Cyperaceae common throughout and *Hydrocotyle vulgaris* pollen present (*circa* 5%) in the peats. Spore values are low (*circa* 5%) except in the uppermost level where there is a marked peak in *Sphagnum* of *circa* 35%. There are no distinctive changes in the pollen spectra across the sedimentary boundary from the top of the carse to peat deposits. The indicative environment is



Palnure (6): Percentage pollen diagram
Borehole: PAL/6
Height: 9.26m O.D.
Grid ref.: NX 44905 63630
Figure 7.3
Trees
Shrubs
Herbs
Spores
Radiocarbon years BP
Lithology
Depth
6,100±70
Alnus
Betula
Pinus
Quercus
Tilia
Ulmus
Coryloid
Hedera
Salix
Poaceae
Cyperaceae
Apiaceae
Anthemis type
Aster type
Silene type
Stellaria type
Chenopodiaceae
Liguliflorae
Filipendula
Hydrocotyle vulgaris
Lythrum type
Rubiaceae
Rumex acetosella/acetosa
Filicales
Lycopodium selago
Polypodium
Pteridium
Sphagnum
Trees
Shrubs
Herbs
Spores
Unidentified
+ = <1% of species
Analyst: James Wells (5/1997)


Palnure (6): Perentage pollen assemblage
Borehole: Pal6
Height: 9.28m O.D.
Grid ref.: NX 44905 63630
Radiocarbon years BP
Depth
Lithology
Trees
Shrubs
Dwarf shrubs
Herbs
Aquatics
Spores
Betula
Fraxinus
Pinus
Quercus
Sorbus
Ulmus
Coryloid
Hedera
Salix
Calluna
Empetrum
Poaceae
Cyperaceae
Apiaceae
Hydrocotyle vulgaris
Aster type
Chenopodiaceae
Cistaceae
Euphorbiaceae
Fabaceae
Mentha type
Lythrum salicaria
Plantago maritima
Filipendula
Rubiaceae
Rumex acetosella/acetosa
Solanaceae
Potamogeton
Typha latifolia
Filicales
Asplenium marinum
Cystopteris fragilis
Isoetes
Thelypteris palustris
Pteridium
Sphagnum
Trees
Shrubs
Dwarf shrubs
Herbs
Aquatics
Spores
Unidentified
Figure 7.4
Analyst: James Wells (1996)
+ = <1% of species

one of a mixed deciduous woodland with hazel scrub interspersed amongst a relatively open area of grassland. It is probable that the arboreal taxa were growing on the valley sides and the grasses were mainly confined to the flat lands in the centre of the valley. A slight increase in grasses toward the boundary is an acceptable vegetational response to a move from estuarine to terrestrial environments. Saltmarsh plants record no real presence in the pollen record with the possible exception of *Aster* type (Sea Aster?) whose pollen values do fall in the peats. Of further note is relatively low percentage of *Alnus* pollen compared to other carse/peat boundary pollen assemblages such as at Carsewalloch Flow where it is recorded at *circa* 40% (see section 7.4.6). This would indicate that Alder was present in low numbers close to the sample site. A radiocarbon date has consequently been obtained on this regressive contact (6,100±70 ^{14}C years BP - Beta-105932) and is detailed in Table 7.1.

Altitude: -1.19 to -1.04m O.D. [Depth: 1045-1030cm] (Figure 7.4)
The main tree species identified is *Betula* but low values of *Pinus*, *Quercus* and *Ulmus* are also recorded. Tree values range between 20% in the silts and clays to *circa* 10% in the peats. *Alnus* is conspicuously absent. Coryloid values are high at *circa* 40% only falling to *circa* 25% in the peats. Poaceae records a strong presence throughout the sequence with values ranging between 15% and 35% of total pollen. The other main herb taxon group of Cyperaceae records a distinctive increase in numbers from the base of the sequence (4%) into the peats where it peaks at 33% before falling again in the overlying carse sediments to 12% by the uppermost level. Similarly spore values increase into the peats, particularly Filicales and *Thelypteris palustris*. The pollen spectra indicate the presence of extensive hazel scrub with scattered mixed woodland dominated by birch interspersed amongst extensive areas of open grassland. The Alder rise does not appear to be underway. There is no palynological evidence for breaks in sedimentation through the sequence of intercalating buried peat and estuarine sediments. Radiocarbon dates of the lower (regressive) and upper (transgressive) buried peat contacts were therefore determined (8,310±100 ^{14}C years BP [Beta-96327] and 8,190±80 ^{14}C years BP [Beta-96326] respectively) and are detailed in Table 7.1.

7.3.3 Summary of results

The pollen evidence from across the boundaries between the peats and the estuarine sediments at Palnure show no clear signs that there were depositional lacunae. The buried silts and clays which are overlain by buried peats at -1.10m O.D. contain microfauna that indicate, where present, a low intertidal saltmarsh environment of deposition. This confirms further that the change from minerogenic sedimentation to pre-Alder rise peat formation by 8,310±100 ^{14}C years BP was probably uninterrupted at this location.

Rising sea levels resulted in the covering of the peats by the carse (estuarine) muds. The whole sequence of carse deposition at this location took place sometime between 8,190±80 ^{14}C years BP and 6,100±70 ^{14}C years BP. Microfaunal analysis record three distinct phases (all occurring within the lower half of the carse sediments) where the indicated environment records an increase in tidal influence. This resulted in intertidal mudflat conditions, probably at some distance from open marine conditions, interspersed within a sequence that was mainly deposited on a lower saltings terrace.

7.4 Carsewalloch Flow

7.4.1 CWF/A: Foraminifera assemblage (Figure 7.5; Table 7.5)

Foraminifera analysis on the sampled core taken from Carsewalloch Flow has allowed the identification of eleven distinctive phases (Figure 7.5). Details of each phase and the main foraminifera associations are summarised in Table 7.5. Foraminifera abundance is highly variable with a range from 0 to >300 species recovered per level. Approximately 40 species have been identified in total, although, species diversity never exceeds 18 per level. The buried peat deposits and the surface peats were not sampled for foraminifera.

CWF/F/1 -9.35 to -6.53m O.D. [Depth: 1675-1975cm]

The euryhaline *H. germanica* dominates this phase peaking in abundance in the uppermost level. Low but consistent numbers of marine (inner shelf) species including *Cornuloculina balkwilli*, *Quinqueloculina* sp., *Spirillina vivipara* and *Patelina corrugata* are also present. Due to low abundance it is difficult to establish whether these species are allochthonous or *in situ*. Marsh and brackish species are almost absent. The occasional test of *Globigerina* sp., a marine planktonic form, is also recorded. The environmental significance of this assemblage indicates a brackish/marine low estuarine intertidal to subtidal mudflat influenced by open marine conditions.

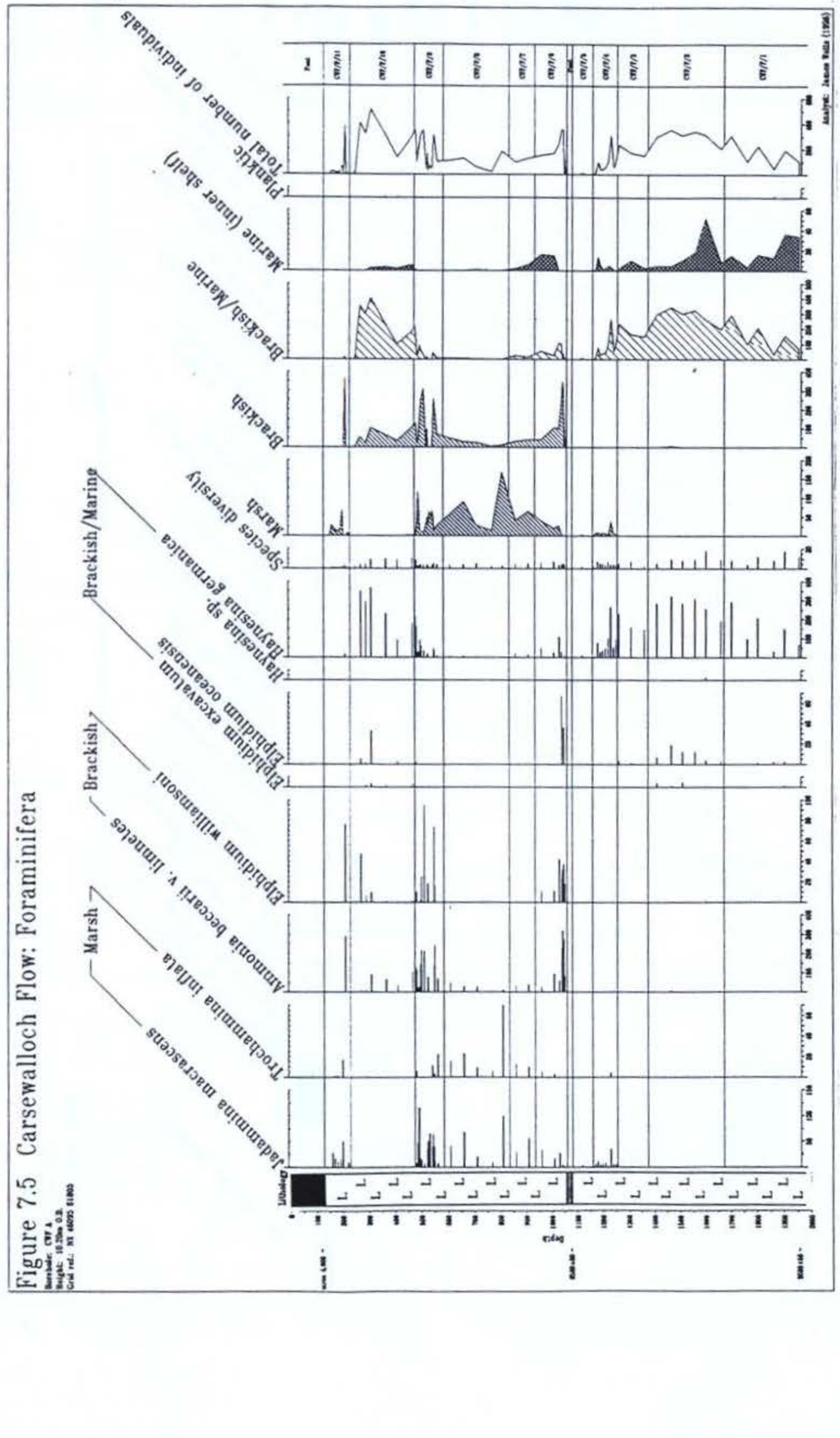
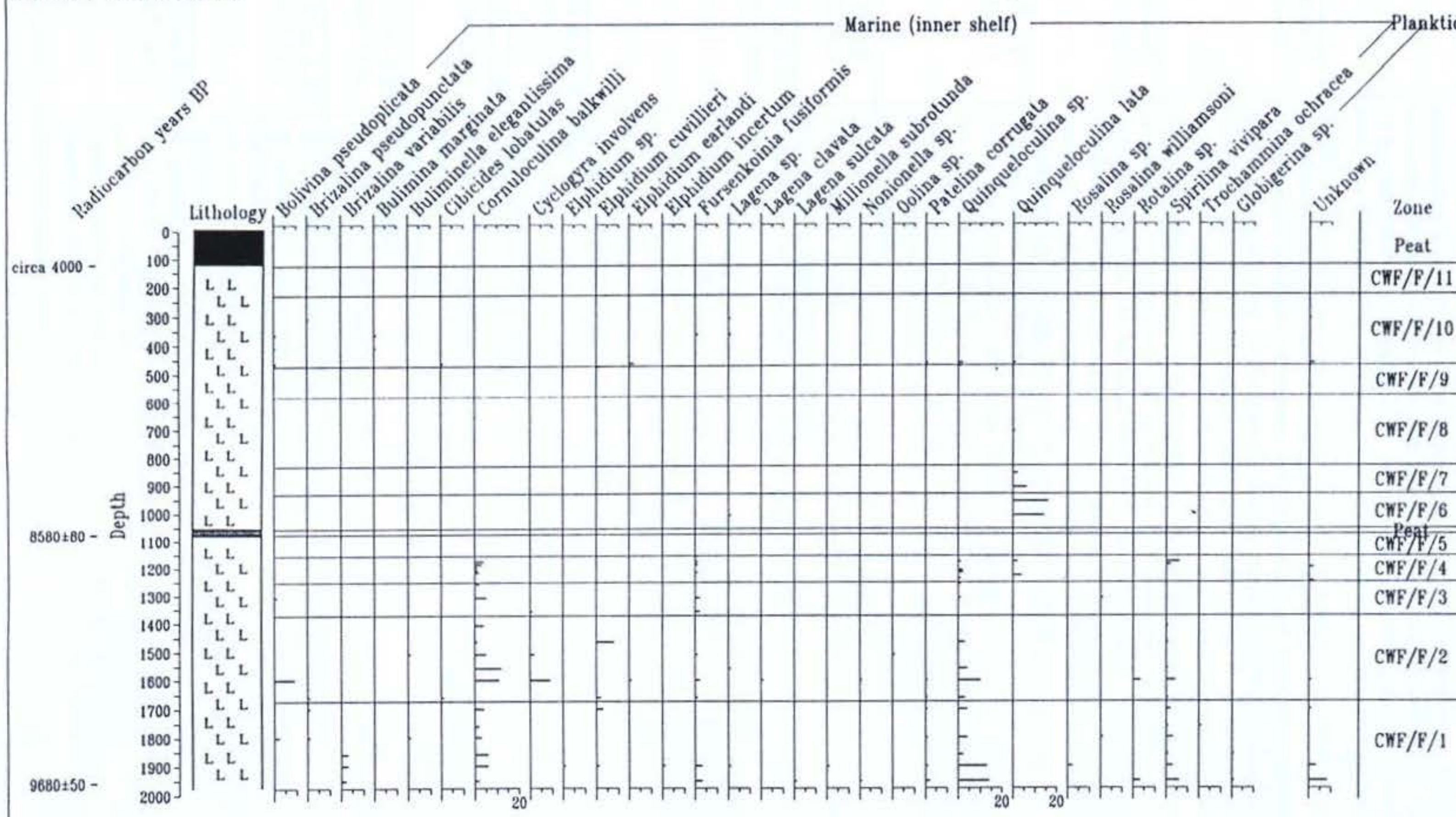


Figure 7.5 Carsewalloch Flow: Foraminifera

Figure 7.5 Carsewalloch Flow: Foraminifera (cont.)

Borehole: CWF A
Height: 10.20m O.D.
Grid ref.: NX 46095 61805



Analyst: James Wells (1996)

CWF Foram. Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of foraminifera phase
CWF/F/11	**8.94-7.92** 128-230	***J. macrescens - T. inflata - A. limnetes - E. williamsoni*** *J. macrescens* values increase throughout the phase prior to the absence of all foraminifera in the silts and clays immediately beneath the surface peats. *T. inflata* is occasionally present. One anomolous level at *circa* 200cm records high values of the two lower marsh species of *A. limnetes* and *E. williamsoni* in conjunction with low numbers of *H. germanica* and the two above mentioned agglutinating species.
CWF/F/10	**7.92-5.47** 230-475	***H. germanica - A. limnetes - E. williamsoni - E. oceanensis*** *H. germanica* dominates throughout increasing in numbers in the upper half of the phase. In the lower half of the phase *A. limnetes* values rise steadily before falling sharply at *circa* 300cm whereupon values of *E. williamsoni, E. oceanensis* and *E. excavatum* all increase. Numbers of marine (inner shelf) species are recorded in all but the uppermost levels. *J. macrescens* records only the occasional presence.
CWF/F/9	**5.47-4.37** 475-585	***A. limnetes - J. macrescens - H. germanica - E. williamsoni - T. inflata*** This phase appears to be transitional with the main species recording marked fluctuations in numbers throughout. *A. limnetes* for the most part dominates the phase, however, *J. macrescens* and *E. williamsoni* are both well represented. In the upper half of the phase values of *H. germanica* increase.
CWF/F/8	**4.37-1.87** 585-835	***J. macrescens - A. limnetes - T. inflata*** In the lowermost level of the phase values of *J. macrescens* and *T. inflata* are high before falling sharply by *circa* 775cm. Values of both species increase to a peak at *circa* 655cm before falling at the top of the phase. Of the other species present only *A. limnetes* is recorded in all levels with values increasing steadily toward the top of the phase.
CWF/F/7	**1.87-0.87** 835-935	***J. macrescens - A. limnetes - T. inflata - H. germanica*** This phase is distinguished from F/8 by the presence of *H. germanica* and the marine (inner shelf) species *Q. lata*.
CWF/F/6	**0.87 to -0.38** 935-1060	***A. limnetes - H. germanica - J. macrescens - E. williamsoni - E. oceanensis - Q. lata*** In the lowermost part of this phase high values are recorded for *A. limnetes, E. williamsoni* and *E. oceanensis*. By *circa* 1030cm, however, each of these species has fallen sharply and particularly *E. oceanensis* which is not recorded again in the phase. *H. germanica* values fluctuate throughout. Numbers of *J. macrescens* and to a lesser degree *T. inflata* increase to the top of the phase. *Q. lata* similarly records a presence in the uppermost levels.
CWF/F/5	**-0.59 to -1.38** 1081-1160	**Barren** The presence of *J. macrescens* and *H. germanica* is recorded in one level of a phase which is otherwise barren of foraminifera.
CWF/F/4	**-1.38 to -2.33** 1160-1255	***H. germanica - J. macrescens*** Values of *H. germanica* are initially high but fall towards the top of the phase. *J. macrescens* is present in consistantly low numbers throughout the phase. Low numbers of marine (inner shelf) species are present.
CWF/F/3	**-2.33 to -3.53** 1255-1375	***H. germanica*** *H. germanica* dominates this phase. *E. oceanensis, C. balkwilli* and *F. fusiformis* all record an occasional presence.
CWF/F/2	**-3.53 to -6.53** 1375-1675	***H. germanica - E. oceanensis - C. balkwilli - Quinqueloculina* sp.** *H. germanica* dominates this phase. *E. oceanensis* is recorded in all levels increasing to a peak at *circa* 1460cm. *E. excavatum* is recorded at low values. Marine (inner shelf) species diversity is high with significant numbers of *C. balkwilli, Quinqueloculina* sp. and *S. vivipara* in most levels.
CWF/F/1	**-6.53 to -9.35** 1675-1957	***H. germanica - C. balkwilli - Quinqueloculina* sp.** This phase is distinguished from F/2 by the near absence of *E. oceanensis*. *H. germanica* fluctuate throughout however the broad trend is one of increasing numbers to the uppermost levels. The diversity and abundance (particularly in the lowermost half of the phase) of the marine (inner shelf) species is high of which the main species are as for F/2.

Table 7.5 Main characteristics of foraminifera phases in core CWF/A, Carsewalloch Flow

CWF/F/2 -6.53 to -3.53m O.D. [Depth: 1375-1675cm]

As in the previous phase, *H. germanica* dominates the assemblage and the marine (inner shelf) species including *C. balkwilli*, *Quinqueloculina* sp., *S. vivipara* and *P. corrugata* remain present in low numbers. However, the increased presence of the two brackish/marine species of *E. oceanensis* and *Elphidium excavatum* type distinguishes this phase from the previous one. Whether this represents a period of changing water depth is uncertain. The reduction in the number of marine (inner shelf) species probably indicates that the foraminifera association correlates with a low estuarine intertidal mudflat.

CWF/F/3 -3.53 to -2.33m O.D. [Depth: 1255-1375cm]

Although *H. germanica* remains dominant, species abundance and diversity fall in this phase with no other species recording a presence in every level. This foraminifera association, however, probably continues to indicate a low estuarine intertidal mudflat environment of deposition.

CWF/F/4 -2.33 to -1.38m O.D. [Depth: 1160-1255cm]

A number of marine (inner shelf) species retain a presence in this phase (e.g. *C. balkwilli*, *Quinqueloculina* sp. and *Fursenkoina fusiformis*), however, falling numbers of *H. germanica* and the marked presence of the marsh species *J. macrescens* characterise this phase. This change in assemblage composition clearly marks a shallowing of water depth and the close proximity of a vegetated saltmarsh. The absence of brackish species is noticeable and may indicate an open marine influence with regular salinity fluctuations. It is suggested that the foraminifera assemblage of this phase is indicative of a lower saltings terrace possibly in the lowermost part of the estuary.

CWF/F/5 -1.38 to -0.59m O.D. [Depth: 1081-1160cm]

One level in this phase records a presence of both *J. macrescens* and *H. germanica* - otherwise this section of the sequence that lies immediately below the buried peat deposits is barren of foraminifera. Whether this absence is a consequence of *post mortem* destruction or that the environment at the time of deposition was not conducive to habitation by foraminifera (e.g. altitude above mean tide level) is unclear. If this is the case then the indicated environment is of a high intertidal saltmarsh and would imply that there was no hiatus in the sequence and the transition to terrestrial peats was probably gradual.

CWF/F/6 -0.38 to 0.87m O.D. [Depth: 935-1060cm]

In the sediments that lie immediately above the buried peat/organic rich deposits the foraminifera assemblage is distinctive with high values of the brackish species *A. limnetes* and to a lesser degree *E. williamsoni* and the brackish/marine species of *E. oceanensis* and *H. germanica*. Agglutinating foraminifera (*J. macrescens*) are rare and marine (inner shelf) species initially do not record a presence. This association probably represents an intertidal mudflat environment.

By mid-phase, however, both *A. limnetes* and *E. williamsoni* values have fallen sharply although they are still well represented, *E. oceanensis* is not recorded and the agglutinating marsh species of *J. macrescens* and *T. inflata* have increased in numbers. *Haynesina germanica* remains present in relatively high numbers and the introduction of the marine (inner shelf) species *Quinqueloculina lata* is distinctive. This association of species suggests a transition to a very brackish intertidal lower saltings terrace possibly with *Spartina*.

CWF/F/7 0.87 to 1.87m O.D. [Depth: 835-935cm]

This phase is distinguished from the previous one by falling numbers of the probably allochthonous marine (inner shelf) *Quinqueloculina* species, the disappearance of *E. williamsoni* and the increase in the marsh species *J. macrescens* and *T. inflata*. *Ammonia limnetes* and *H. germanica* are both present but their values are lower than the previous phase. With *A. limnetes* and *J. macrescens* both recording similar numbers establishing the depositional environment is difficult but is probably a transitional phase between an intertidal mudflat and a lower saltings terrace.

CWF/F/8 1.87 to 4.37m O.D. [Depth: 585-835cm]

Haynesina germanica is absent from the lower half of the phase and records only an occasional presence toward the upper levels. *Ammonia limnetes* similarly is recorded in low numbers in the lower half of the phase before increasing in the upper half. These two changes may indicate an increase in salinity in the uppermost levels of this phase. The dominance of the agglutinating species *J. macrescens* and *T. inflata*, however, suggests an environment of a lower saltings terrace. Marine (inner shelf) species are absent apart from one record of *Q. lata*.

CWF/F/9 4.37 to 5.47m O.D. [Depth: 475-585cm]

With dramatic fluctuations in the representation of all the main species this phase suggests a rapidly changing depositional environment. The two marsh foraminifera species *J. macrescens* and the less well represented *T. inflata* fluctuate sharply throughout the phase but the overall trend indicates a fall in numbers in the uppermost levels. *Ammonia limnetes* continues its increase in values into this phase, however, as with the now present *E. williamsoni* both species show a wide range in representation. The brackish/marine *H. germanica* reveals a clearer trend rising in values throughout the phase to be the most well represented species in the uppermost levels. There is a synchronous occurrence of additional brackish/marine species (*E. excavatum* type and *E. oceanensis*) and the introduction of marine (inner shelf) species (e.g. *Quinqueloculina* sp.).

Although the changes of environment indicated by the foraminifera assemblage in this phase are somewhat sporadic the overall trend of a lowering in the tidal regime (relative to Mean Sea Level) is evident. The transition from a low intertidal saltmarsh to a high intertidal mudflat at the top of the phase is clear. A dynamic change in depositional environment such as is recorded here may reflect a rapidly rising relative sea-level.

CWF/F/10 5.47 to 7.92m O.D. [Depth: 230-475cm]
Haynesina germanica remains the dominant species in this phase. In the first half of the phase *A. limnetes* is represented in high numbers with both *J. macrescens* and *E. williamsoni* recording a low presence in all levels. By the upper half of the phase numbers of *A. limnetes* have fallen and the presence of *E. williamsoni*, *E. excavatum* type and *E. oceanensis* all increase to low but significant levels. A small number of marine (inner shelf) species are recorded and are probably allochthonous. The change in faunal composition mid-phase probably reflects a change from a high to a low intertidal mudflat with an assemblage similar to CWF/F/2.

CWF/F/11 7.92 to 8.94m O.D. [Depth: 128-230cm]
The start of this phase is marked by the absence of foraminifera. The presence in one level of high numbers of *A. limnetes* and *E. williamsoni* and low values of *H. germanica* are anomalous in a phase dominated by the agglutinating species *J. macrescens* and *T. inflata*. By the top of the phase, immediately prior to the boundary with the overlying peat deposits, the sediments are barren of foraminifera. After the intertidal mudflat conditions of the previous phase there is a transition to a lower saltings environment. Whether the rapidity of this change is representative of an hiatus in the depositional sequence is unclear. The absence of foraminifera in the uppermost levels of the phase is, as previously speculated (CWF/F/5), probably due to either increased altitude above mean sea level (i.e. a higher saltings terrace) or poor

preservation of tests. There is no evidence to suggest that the change to peat formation was not gradual.

7.4.2 CWF/A: Ostracod analysis (Figure 7.6; Table 7.6)

Ostracod analysis on the sampled core taken from CWF/A has allowed the identification of eight phases (Figure 7.6). Summarised details of each phase and the main ostracod associations are presented in Table 7.6. Thirty two ostracod species have been identified but of these the brackish estuarine *L. castanea* is the dominant species in all but two levels in which ostracods were recorded. *Leptocythere lacertosa* is as common but is never recorded in the numbers of the previous species. Ostracod abundance and species diversity are generally high in the sediments beneath the buried peat deposit but are relatively low in the overlying sediments. The buried and surface peats were not sampled for ostracods.

CWF/O/1 -9.35 to -7.60m O.D. [Depth: 1782-1957cm]

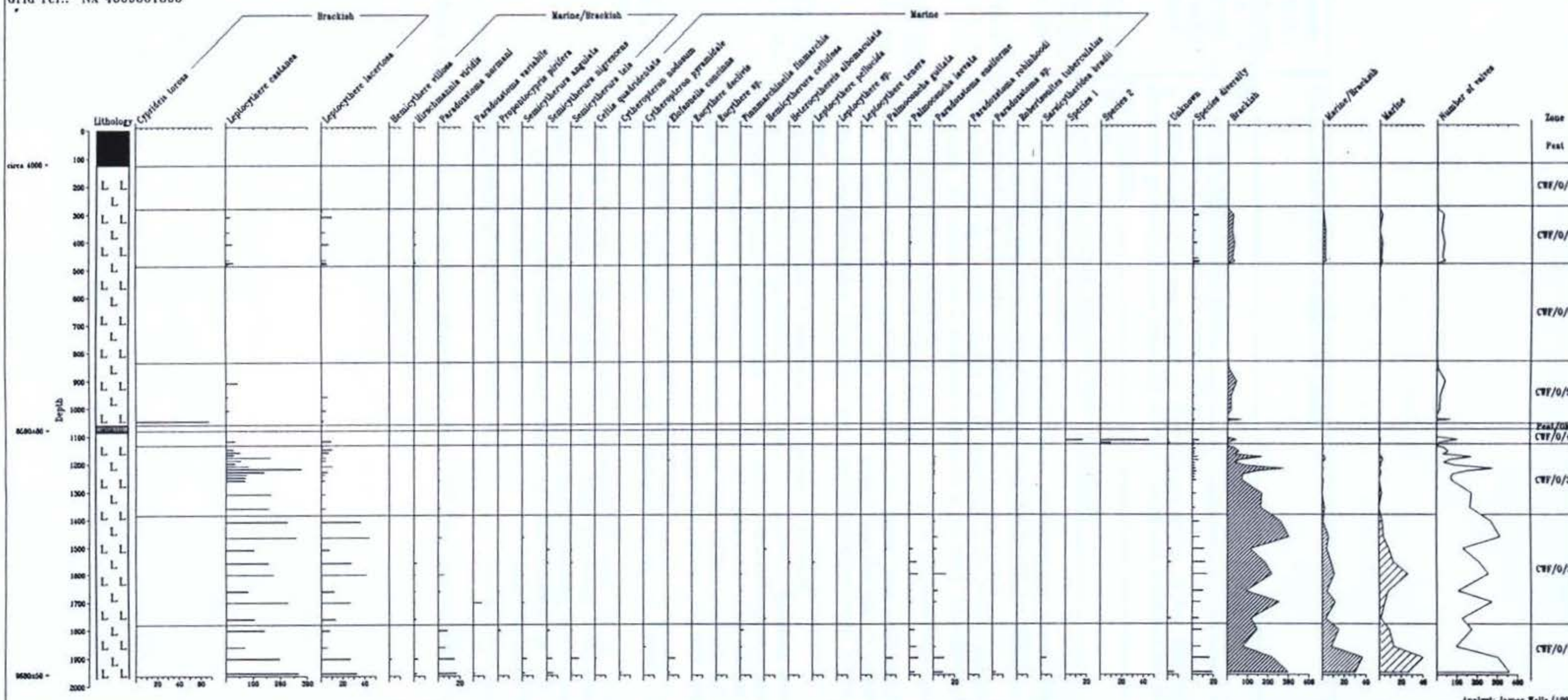
Leptocythere castanea clearly dominates this phase although valve concentrations are variable and fall mid-phase. Species diversity is high (relative to all succeeding phases in this borehole), particularly in the lowermost half of the phase, with both brackish and marine species including *L. lacertosa*, *Paradoxostoma normani*, *P. laevata*, *Semicytherura* sp. and *Paradoxostoma ensiforme* all present in low but consistent numbers. The assemblage correlates well with living associations from contemporary estuaries in the British Isles (see Athersuch *et al.*, 1989) indicating water temperatures not dissimilar to the present. The two species *Elofsonella concinna* and to a greater degree *Finmarchinella finmarchica*, whose present distribution is north of the British Isles, may indicate slightly colder water temperatures. It is probable, however, that the valves of the colder water species recorded in this phase were reworked from older (Lateglacial) sediments. The assemblage is suggestive of a low intertidal or possibly subtidal mudflat environment of deposition close to open marine conditions.

CWF/O/2 -7.60 to -3.63m O.D. [Depth: 1385-1782cm]

The dominant *L. castanea* fluctuates in numbers throughout the phase as does *L. lacertosa* which appears to have increased in values relative to the previous phase. The marine/brackish and marine species have fallen in numbers and diversity in this phase, however, *P. ensiforme*, *P. laevata* and *P. normani* retain a presence and reach a peak mid-phase. The environment of deposition is more probably that of a low intertidal mudflat with shallowing water depth or alternatively an increase in distance form open marine conditions.

Figure 7.6 Carsewalloch Flow: Ostracods

Borehole: CWF A
Height: 10.20m O.D.
Grid ref.: NX 4609561805



CWF Ostracod Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of ostracod phases
CWF/O/8	**8.94 to 7.42** 128-280	**Barren** No ostracods present in this phase.
CWF/O/7	**7.42 to 5.35** 280-487	***L. castanea - L. lacertosa - H. viridis - P. laevata*** *L. castanea* and to a lesser degree *L. lacertosa* are present in low numbers. Occasional presence of other species of which *H. viridis* and *P. laevata* are the most common.
CWF/O/6	**5.35 to 1.87** 487-835	**Barren** Occasional valve recorded. Otherwise barren of ostracods.
CWF/O/5	**1.87 to -0.38** 835-1060	***C. torosa - L. castanea - L. lacertosa*** *C. torosa* dominates the level immediately above the buried peat deposit after which *L. castanea* dominates in low numbers; *L. lacertosa* records a presence.
CWF/O/4	**-0.59 to -1.13** 1081-1135	***Species 1 and 2 - L. castanea - L. lacertosa*** Two unidentifed species are recorded in the lower half of the phase - probably freshwater. *L. castanea* and *L. lacertosa* are present in one level. The upper half of the phase is barren of ostracods.
CWF/O/3	**-1.13 to -3.63** 1135-1385	***L. castanea - L. lacertosa - Paradoxostoma* sp.** The abundance of *L. castanea* falls throughout the phase from >200 to <50 individual valves. *L. lacertosa* remains present in low values that slightly increase toward the top of the phase. *P. normani* and *P. ensiforme* both regularly record a presence.
CWF/O/2	**-3.63 to -7.60** 1385-1782	***L. castanea - L. lacertosa - P. ensiforme - P. laevata - P. normani*** Fluctuating numbers of the dominant *L. castanea* and common *L. lacertosa* reflect the variable ostracod concentrations in this phase. Brackish/marine species diversity is high with *H. viridis*, *P. normani* and *Semicytherura* sp. recording regular presence. Marine species diversity is also high. Of note are peaks in the two common species of *P. laevata* and *P. ensiforme* mid-phase. The cold water form *F. finmarchica* records a presence in some levels.
CWF/O/1	**-7.60 to -9.35** 1782-1957	***L. castanea - L. lacertosa - P. normani - Semicytherura* sp. - *P. laevata - P. ensiforme*** *L. castanea* dominates this phase, however, numbers fall toward the top of the phase. *L. lacertosa* similarly falls in numbers in the upper half of the phase. Species diversity is high, particularly in the lower half of the phase, with the main other species being *P. normani*, *Semicytherura* sp., *Palmoconcha* sp. and *P. ensiforme*. A presence of *F. finmarchica* and *E. concinna* possibly indicate colder water temperatures than at present.

Table 7.6 Main characteristics of ostracod phases in core CWF/A, Carsewalloch Flow.

CWF/O/3 -3.63 to -1.13m O.D. [Depth: 1135-1385cm]

Values of *L. castanea* fall throughout the phase. *Leptocythere lacertosa* remains present in low numbers. *Paradoxostoma normani* and *P. ensiforme* both record a presence in many of the levels in this phase. In general, however, few other species occur. These characteristics probably indicate a relative shallowing of the environment of deposition indicating a higher intertidal mudflat. The near absence of marine/brackish and marine species probably reflect a further increase in distance of the location from open marine conditions.

CWF/O/4 -1.13 to -0.59m O.D. [Depth: 1081-1135]

Only two levels record the presence of ostracods in this phase which is otherwise barren. Both *L. castanea* and *L. lacertosa* are recorded in one of these, however, it is two other unidentified species that distinguish this phase from the last. The unknown species' ecology remains uncertain but are probably freshwater. The paucity of brackish and marine species probably indicates the change to an intertidal marsh environment prior to the terrestrial peat formation - an environment in which these species are commonly absent. Alternatively ostracods may not have been preserved in the sediments.

CWF/O/5 -0.38 to 1.87m O.D. [Depth: 835-1060cm]

In this phase, which overlies the buried peat deposits, ostracods are present but never abundant with total number of valves never exceeding 65 per level. In the level that contains ostracoda above the peat *C. torosa* is recorded as the only species - its euryhaline tolerance indicating little about the environment. The rest of the phase contains low frequencies of *L. castanea* and *L. lacertosa.* No other species are recorded. These low numbers probably indicate a depositional environment of a well protected high intertidal mudflat.

CWF/O/6 1.87 to 5.35m O.D. [Depth: 487-835cm]

This phase is barren of ostracods possibly indicating a saltmarsh environment from which ostracods are commonly absent.

CWF/O/7 5.35 to 7.42m O.D. [Depth: 280-487cm]

Ostracod values never exceed 50 individual valves per level in this phase. *Leptocythere castanea* and *L. lacertosa* once again are the main species represented and are complemented by the occasional presence of marine/brackish and marine species including *Hirschmannia viridis* and *P. laevata* - an association of species indicative of an intertidal mudflat.

CWF/O/8 (7.42 to 8.94m O.D.)
As for CWF/O/6 this phase is barren of ostracods.

7.4.3 CWF/A: Diatom analysis (Figure 7.7)

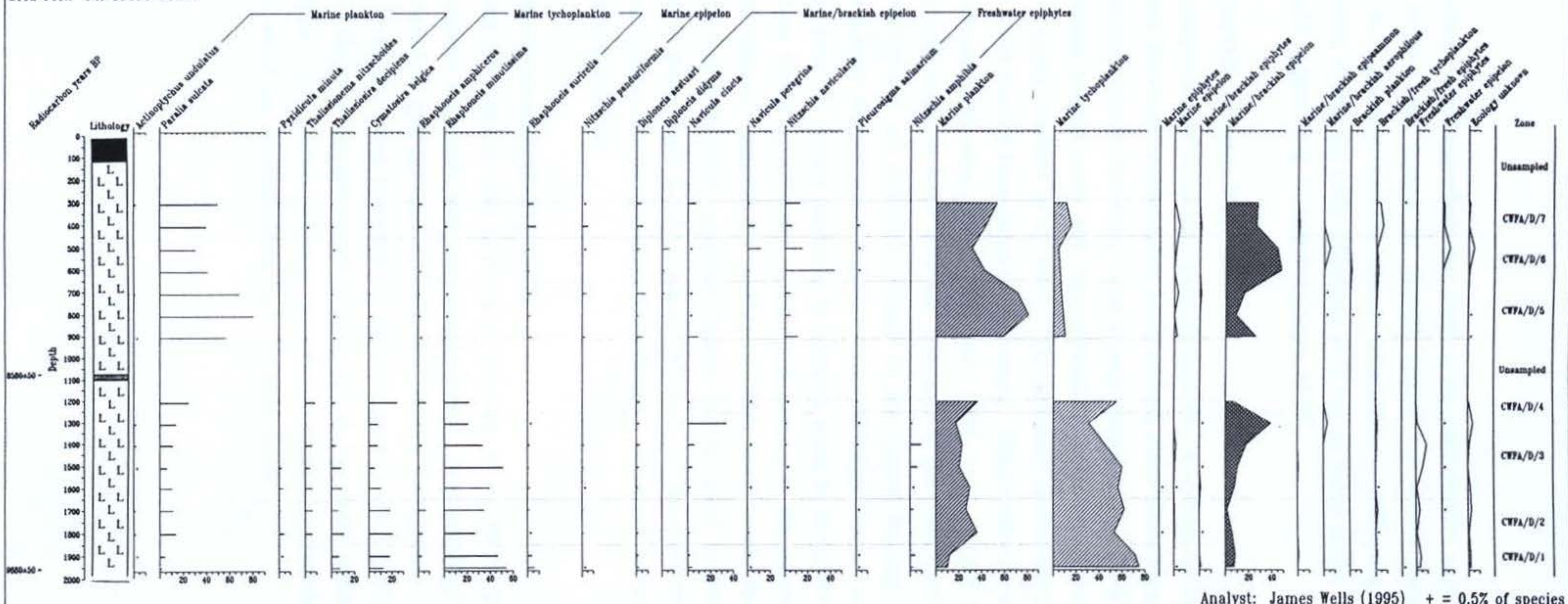
Samples were selected for diatom analysis at widely spaced intervals of *circa* 1m throughout the silty clays at this site to characterise the sediments. The results were then compared with the findings of the more detailed foraminifera and ostracod analyses over the same sediments in order to determine the ability of diatom analysis to establish accurately changing environments of deposition. Only sixteen samples were analysed of which all contained diatoms. At least 71 species have been identified. The results presented in Figure 7.7 have not been zoned but are described below in two sections detailing firstly the diatom populations in the early Flandrian estuarine silts and secondly those in the mid-Flandrian carse sediments.

Altitude: -9.35 to -1.78m O.D. [Depth: 1198-1957cm]

The marine tychoplanktonic species of *Raphoneis (Delphineis) minutissima* and *Cymatosira belgica* are the dominant species in the diatom assemblages of the buried silts. The marine planktons *Paralia sulcata*, *Thalissiosira decipiens* and *Thalissionema nitzschoides* are also well represented throughout these sediments. Other species that are represented in low numbers (*circa* <5%) but which are present in most levels include *Pyxidicula minuta*, *Raphoneis amphiceros*, *Raphoneis surirella*, *Diploneis aestuari*, *Navicula cincta* and the freshwater epiphyte *Nitzschia amphibia*. The summary diagram shows little evidence for a distinctive change of environment although the gradually falling trend from *circa* 75-35% of the marine tychoplanktons toward the uppermost levels of the sediments at *circa* -2m O.D. is noticeable. The overwhelming dominance of this diatom lifeform group in the lowermost two levels (*circa* -9.3 to -8.8m O.D.) is also clear. A peak in marine/brackish epipelon species is recorded due to an increase in one level of the presence of *Navicula cincta*. This was probably a result of a bloom in this species and is therefore not considered to be of significance. The indicative environment of these diatom assemblages, using Vos and de Wolf (1993), could be either sub-tidal mudflats, inter-tidal mudflats or supra-tidal saltmarshes; but probably not sand-flats. Interestingly, and paradoxically, G. Underwood (pers. comm.) has noted *R. minutissima* as living where the substrate is generally sandier - this would certainly appear to be the case here (see particle size analysis below in 7.4.4). Nonetheless, the broad consistency of the diatom assemblages throughout these sediments relates well with the unchanging foraminifera and ostracod populations throughout the same

Figure 7.7 Carsewalloch Flow: Diatoms (selected taxa only)

Borehole: CWF/A
Height: 10.22m O.D.
Grid ref.: NX 46095 61805



levels. Further, it has been noted elsewhere that both of the main species here, *R. minutissima* and *C. belgica*, are known to flourish during the winter months (Underwood, 1994). It is possible that this diatom association is indicating that marine water temperatures during the early Flandrian were not as warm as the land climatic indicators would suggest (e.g. Bishop and Coope, 1977).

Altitude: 1.12 to 7.12m O.D. [Depth: 908-308cm]
The difference in the composition of the diatom population of the carse from the early Flandrian silts is marked. *Raphoneis minutissima* never exceeds *circa* 3% of the total and *P. sulcata*, the marine plankton, dominates with a range between *circa* 30-80%. Of all the other species present only the marine/brackish epipelon *Nitzschia navicularis* is recorded in any numbers in all levels. The summary diatom diagram does appear to record some phasing throughout the sediments. The dominance of *P. sulcata* is clearly checked between *circa* 3.7 and 5.7m O.D. where the marine/brackish epipelon increase to *circa* 40% and a number of the more brackish and freshwater lifeform groups are recorded. Based on the diatom ecology this change would indicate a shallowing of water depth (or increased height above a mean sea level). Above this level *P. sulcata* increases in numbers again to dominate the diatom population which would by inference indicate a deepening in the sequence. The foraminifera and ostracod assemblages throughout these same levels record clearly that where the marine/brackish epipelon species are recorded in greater abundance an increase in water depth is taking place. Where *P. sulcata* maintains a majority of the diatom population the foraminifera indicate a vegetated saltmarsh (saltings) environment of deposition.

7.4.4 CWF/A: Particle size analysis (Figure 7.8)

Samples were selected for particle size analysis at intervals of 5, 10 or 20cm throughout the minerogenic sediments with each sample broadly corresponding with those taken for foraminifera and ostracod in order to facilitate correlation. The foraminifera phases have also been indicated to aid correlation. The results are presented in Figure 7.8 showing the percentages of clay, silt and , the modal and mean particle sizes and Span. In addition selected particle size frequency curves are included. The results, which are detailed below, have not been zoned.

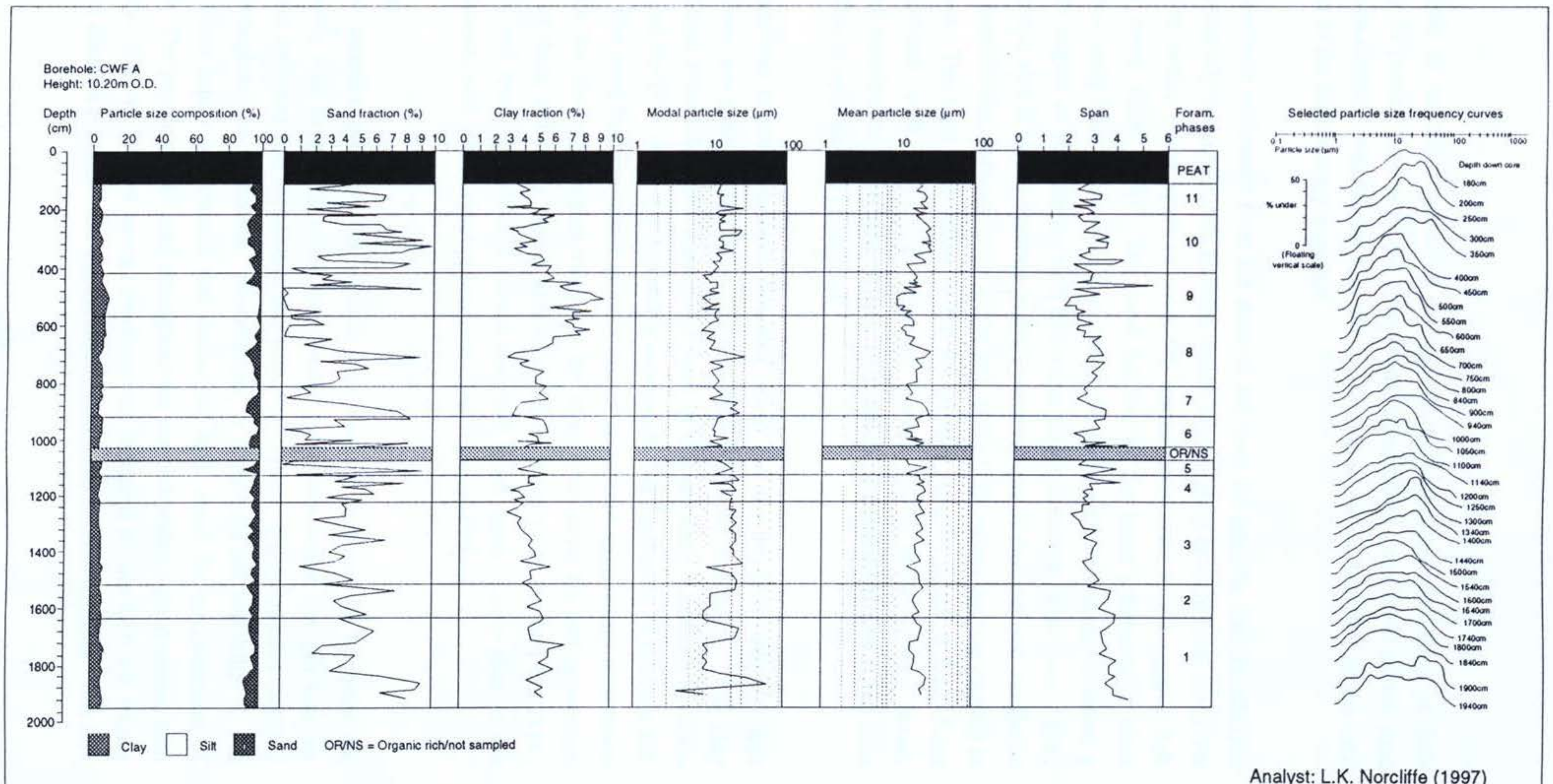


Figure 7.8 Particle size characteristics of borehole CWF/A

Results

The analysis of estuarine sediments throughout the core show that there is little variability in particle size with silt comprising consistently *circa* 85% of the total minerogenic content. Neither the clay nor sand components exceed 10% of the total in any part of the sedimentary sequence.

In the lowermost sediments from the base of the core the particle size distribution shows a relatively consistent clay fraction which falls slightly up-core from *circa* 5% to *circa* 3% before rising again to *circa* 5% immediately prior to the organic rich layers (at *circa* -0.5m O.D.). The sand fraction in the same sediments is more variable but rarely falls below 4%. In contrast, the mean particle size curve shows a remarkable degree of consistency with this value rarely deviating from *circa* 20µm. Modal particle size is highly variable in the lowermost 5m of the core but, similar to the mean particle size, between *circa* -4.5m and -0.5m O.D. values are consistently at *circa* 20µm. The high sand values in the lowest four samples (*circa* -8.5 to -9.5m O.D.) combines with distinctive frequency curves which show a very broad, multimodal distribution. This pattern may well indicate a close proximity at the time of deposition to open marine conditions.

In the uppermost (carse) sediments, between *circa* -0m and 9m O.D., the clay and sand fractions are considerably more variable than the lower sediments. The clay fraction ranges from 3% to 6% throughout most of this sequence, however, between *circa* 3m and 5m O.D. there is a distinctive increase in this fraction up to between 6% and 9%. The sand fraction values broadly record an inverse relationship with those outlined for the clay with higher values in the lowermost *circa* 4m and uppermost *circa* 3m of these sediments falling almost to 0% between *circa* 3m and 5m O.D.. The modal and mean particle size curves correlate much more closely than in the lower sediments with values ranging between *circa* 10µm and 20µm.

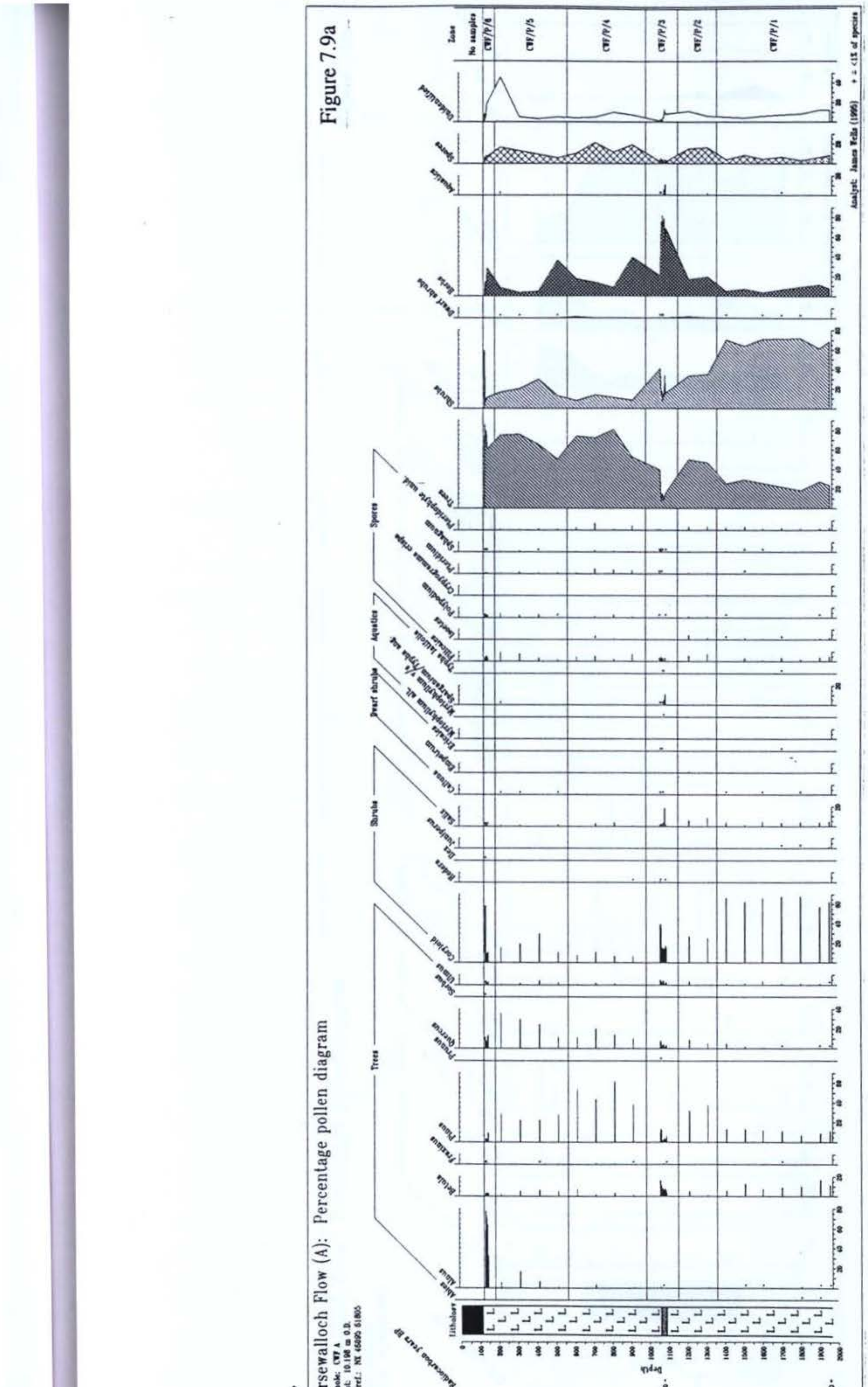
Discussion

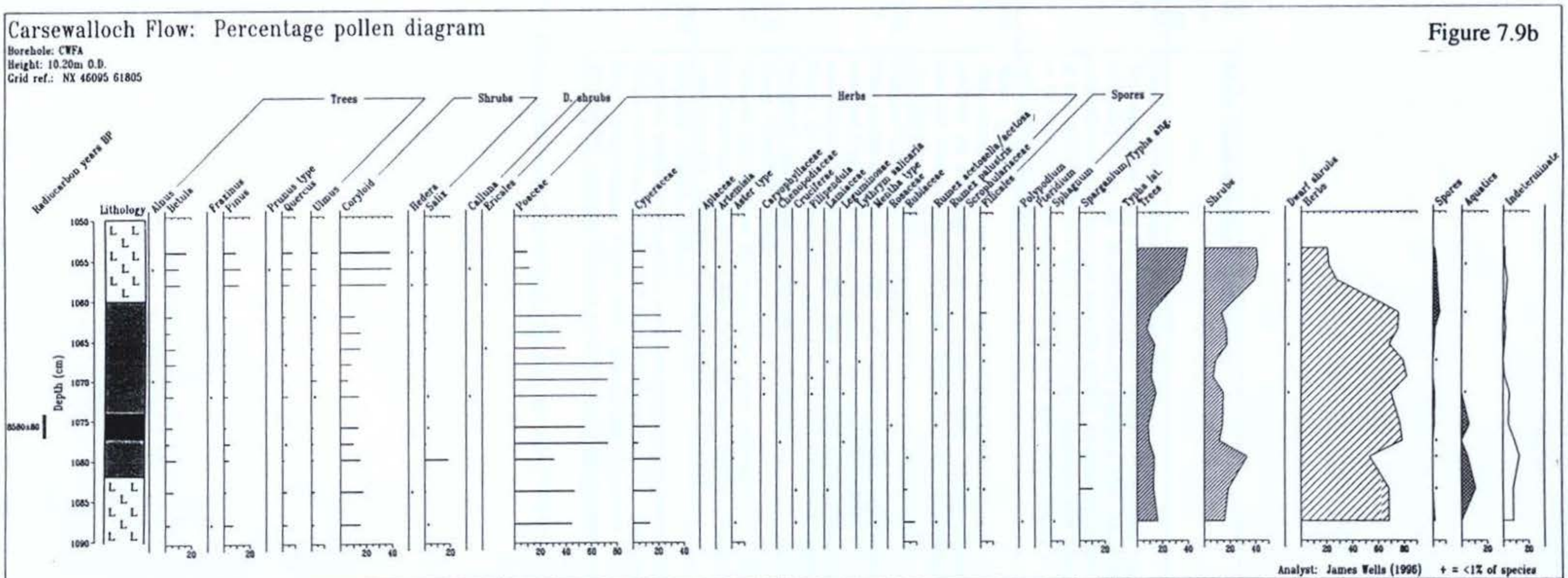
All of the samples prepared for particle size analysis indicate the samples are predominantly silts suggesting either quiet water conditions and/or that silt was the predominant sediment size supplied to this estuarine system. Values of sand and clay are low throughout the sediments. Nonetheless, it is perhaps the variability in the values of these minor constituents that reveal the most about the environments of deposition. The percentage of sand throughout the core is notably more dynamic than that of clay. Clearly the low energy environment indicated by the high silt values would have allowed for sand to be preferentially preserved in the sediments. The less dynamic fluctuations of the clay content probably indicates that the clay particles were able to remain in suspension for longer periods resulting in an "averaging out" effect of clay content (Hjulstrom, 1939). Alternatively, the relative "steadiness" of the clay percentages could be a result of a low degree of cohesion of the fine grained sediments which would have allowed for their continual reworking. This might be the case if, for example, the sediment underwent minimal compaction and consolidation at the time of deposition such as under shallow water conditions where the sediment was not regularly desiccated.

Foraminifera phases have been included to allow for some broad correlation and it is clear that where sand content increases and clay content falls then the foraminifera indicate an estuarine environment of deposition lower in the intertidal zone. Where clay values are higher (e.g. between *circa* 3m and 5m O.D.) then a high saltmarsh (saltings) environment is indicated by the foraminifera.

7.4.5 CWF/A: Pollen analysis (Figures 7.9a and 7.9b; Table 7.7)
Samples were selected for pollen analysis at widely spaced intervals of 1m throughout the silty clays at this site to establish the suitability and potential of these estuarine deposits for vegetational reconstruction. A closer sampling interval (4-2cm) was adopted across the boundaries between minerogenic and peat deposits. Six zones have been identified from the sequence and are shown in Figure 7.9 although due to the close sampling across the buried peats the pollen data for zone CWF/P/3 has been reproduced in Figure 10 for greater detail. Summarised details of each pollen zone and the main pollen associations are presented in Table 7.10.

CWF/P/1 -9.35 to -3.38m O.D. [Depth: 1358-1957cm]
Coryloid values are high throughout the zone ranging between *circa* 55% and 65% of TLP. Both *Betula* and *Pinus* are well represented at *circa* 10%. *Ulmus*, *Salix*, Poaceae and Cyperaceae all record a low presence in each level of this zone. The indicative environment is one of an extensive a probably dense hazel scrub with some birch, pine elm and willow trees present. Interestingly *Alnus* pollen is present in a number of the levels indicating that, although the sediments were deposited prior to the alder rise, it is possible that some *Alnus* were present within the region at this time. Spore values are low throughout the zone never exceeding 12% of TLP comprised mainly of Filicales. Low and stable numbers of unidentified grains are present.


Carsewalloch Flow (A): Percentage pollen diagram
Figure 7.9a
Trees
Shrubs
Dwarf shrubs
Aquatics
Spores
Alnus
Betula
Fraxinus
Pinus
Quercus
Ulmus
Corylus
Hedera
Ilex
Juniperus
Salix
Calluna
Empetrum
Ericales
Sparganium/Typha a/g
Typha latifolia
Filicales
Polypodium
Sphagnum
Trees
Shrubs
Dwarf shrubs
Herbs
Aquatics
Spores
Undifferentiated
Zone
No samples
CWF/P/6
CWF/P/5
CWF/P/4
CWF/P/3
CWF/P/2
CWF/P/1
Lithology
Depth
Analyst: James Wells (1995)
+ = <1% of species



Carsewalloch Flow: Percentage pollen diagram
Figure 7.9b
Borehole: CWFA
Height: 10.20m O.D.
Grid ref.: NX 46095 61805
Trees
Shrubs
D. shrubs
Herbs
Spores
Radiocarbon years BP
Lithology
Alnus
Betula
Fraxinus
Pinus
Prunus type
Quercus
Ulmus
Coryloid
Hedera
Salix
Calluna
Ericales
Poaceae
Cyperaceae
Apiaceae
Artemisia
Aster type
Caryophyllaceae
Chenopodiaceae
Cruciferae
Filipendula
Lamiaceae
Leguminosae
Lythrym salicaria
Mentha type
Rosaceae
Rubiaceae
Rumex acetosella/acetosa
Rumex palustris
Scrophulariaceae
Filicales
Polypodium
Pteridium
Sphagnum
Sparganium/Typha ang.
Typha lat.
Trees
Shrubs
Dwarf shrubs
Herbs
Spores
Aquatics
Indeterminate
Depth (cm)
Analyst: James Wells (1996)
+ = <1% of species

CWF/A Pollen Zones	Altitude (m O.D.) Depth (cm)	Main characteristics of pollen zone
CWF/P/5	**6.62 to 8.42** 358-178	***Pinus* - *Quercus* - *Alnus* - (Poaceae) - *Betula*** Tree dominated zone with *Pinus* values falling to *circa* 25%, *Quercus* values increasing to 38% and *Betula* consistantly present at 5%. *Alnus* values increase markedly throughout the zone from 2% to 18%. Numbers of Coryloid pollen peak at 30% mid-zone before falling to 15% in the uppermost level. Anomalous peak in Poaceae in the lowermost level at *circa* 30% before falling to <5% for the remainder of the zone.
CWF/P/4	**0.42 to 6.62** 978-358	***Pinus* - *Quercus*** *Pinus* dominates the zone with values ranging between 40 and 60%. *Quercus* numbers are also high reaching a peak of 20%. Falling numbers of *Betula*, Coryloid, Poaceae and Cyperaceae. High spore values (including Filicales and *Pteridium*) at *circa* 20%.
CWF/P/3	**-2.28 to 0.42** 1258-978	**Poaceae - Cyperaceae - Coryloid** Herb species dominate this zone with Poaceae recording a maximum of 78% mid-zone and Cyperaceae values fluctuating between 5% and 35%. Coryloid values are relatively high at *circa* 15%. Tree taxa present in low numbers include *Pinus*, *Betula*, *Quercus*, *Ulmus* and *Salix*. There is also a small but significant peak in the aquatic *Sparganium/Typha angustifolia* species.
CWF/P/2	**-3.38 to -2.28** 1358-1258	***Pinus* - Coryloid - *Betula*** Arboreal taxa dominate this zone. *Pinus* values increase to 35%. Similar but less significant rises in *Quercus* and *Salix* are also recorded. Coryloid and *Betula* values both fall. Numbers of spores increase to *circa* 35%.
CWF/P/1	**-9.35 to -3.38** 1957-1358	**Coryloid - (*Betula*) - (*Pinus*)** Coryloid pollen dominates this zone with values ranging between 55% and 65%. *Betula* and *Pinus* are both well represented at *circa* 10%. Other taxa present in low numbers include *Ulmus*, *Salix*, Poaceae and Cyperaceae. The occasional *Alnus* pollen is present. Filicales are present in low but consistant values.

Table 7.7 Main characteristics of pollen zones in core CWF/A.

CWF/P/2 -3.38 to -2.28m O.D. [Depth: 1258-1358cm]

Although only two levels make up this zone there is a marked change from the previous. Coryloid values have fallen to *circa* 30% and similarly *Betula* values have dropped. *Pinus* values have increased to *circa* 35%. *Quercus*, *Salix*, Poaceae and Cyperaceae values all record a slight rise. Aquatic numbers are all but absent but spore values increase to *circa* 15%. Unidentified grain numbers remain unchanged. It is probable that the vegetational changes from zone CWF/P/2 are more apparent than real. It is possible that numbers of pine trees increased in the area at this time. Saccate pine pollen are, however, known to be over-represented in estuarine environments and it is suggested that this is the case here. A hazel dominated woodland probably remained little altered.

CWF/P/3 -2.28 to 0.42m O.D. [Depth: 978-1258cm]

This zone covers the boundaries between the estuarine sediments and the buried peat layer at this location and has consequently been analysed for pollen with closer sampling intervals. As a result the detail of this pollen zone is not clear in Figure 7.9a and is therefore shown in expanded form in Figure 7.9b. *Betula*, *Quercus*, *Ulmus* and *Salix* are recorded in low numbers in every level. *Pinus* values fall considerably ranging between 2% and 12% over the zone. Coryloid numbers fall in relation to zone 2 but remain stable at *circa* 15% for much of the zone prior to a sharp increase to *circa* 40% in the uppermost levels. Poaceae pollen values show a marked change from the previous zone reaching a maximum of 78% mid-zone before falling in the uppermost levels to *circa* 20% of TLP. Cyperaceae values fluctuate (5-35%) but nonetheless represent in general a marked increase to the previous zone. Other herb species are common and species diversity is relatively high. A small (always <10%) but significant peak in the aquatic *Sparganium/Typha angustifolia* is recorded. The fall in numbers of spores and unidentified pollen to very low values is also marked. The continued presence of a mixed woodland dominated by hazel is indicated, however, the extra local change to terrestrial conditions and peat growth has apparently resulted in the dominance of grasses and sedges. It is probable therefore that the herb species were flourishing on the newly exposed land surface of the former estuarine mudflats and that the hazel woodland was restricted in the main to the valley sides.

There is no indication from the pollen record in this zone that there was a distinctive depositional lacunae between the buried peats and the organic silts. Therefore one sample was sent for radiocarbon dating for use as a relative sea-level index point.

The full details of this date (8,580±80 ^{14}C years BP - Beta-96325) are provided in Table 7.1.

CWF/P/4 0.42 to 6.62m O.D. [Depth: 358-978cm]
Pinus pollen return in high numbers throughout this zone ranging between *circa* 40% and 60%. As was previously mentioned pine pollen are commonly preferentially preserved in aquaeous environments, however, it is also probable here that pine was comprising a significant part of the local woodland. Similarly *Quercus* values increase to a peak of *circa* 20% of TLP indicating an increased presence of this species also. In contrast there are significant falls in value for *Betula* (<7%), Coryloid (*circa* 10%), Poaceae (*circa* 7%) and Cyperaceae (*circa* 2%). Herb values are high in one level due to the anomolously high numbers of Chenopodiaceae pollen recorded - these species are common to salt marsh environments and were probably growing on the saltings terraces above Mean High Water of Spring Tides. Spore values increase to *circa* 20% of TLP with Filicales, *Pteridium* and an unidentified Pteridophyte spore all featuring strongly. This increase might suggest that climate was wetter than in previous zones and/or that these species were living in and around the nearby woodlands. Alternatively the change in vegetation composition from a hazel to an oak and pine dominated woodland may have provided more conducive to the development of these species.

CWF/P/5 6.62 to 8.42m O.D. [Depth: 178-358cm]
Pinus values fall to *circa* 25%, *Quercus* values continue to increase to 38% by the top of the zone and Coryloid values peak mid-zone at *circa* 30% before falling to 15% in the uppermost level. *Betula* values remain stable at *circa* 5% of TLP. Significantly *Alnus* values rise considerably in this zone from 2% to a maximum of 18%. Apart from an initial anomalous peak of 30% Poaceae values fall to <5% of TLP for the remainder of the zone. Herb values and species diversity are in general low. Aquatics and dwarf shrubs remain all but absent. Spore values record little change from the previous zone as do the unidentified pollen numbers apart from in the uppermost level where a marked peak is recorded. The composition of the vegetation indicated by the pollen is one of a mixed woodland of which pine, oak and hazel are the main components. Throughout this zone, however, the rise in importance of *Alnus* pollen is noticeable and it is probable that this represents the Alder rise recorded elsewhere in the Cree estuary region (i.e. Brighouse Bay - Chapter 5). It is possible that the slight fall in numbers of pine may indicate that alder is out competing this taxon as it expands - this relationship is a common aspect of the alder rise (see Bennett, 1984). The low values of grass and other herbs suggest that the

forest cover was relatively dense and that the area of the estuarine saltings at this time was at a minimum.

CWF/P/6 8.42 to 9.02m O.D. [Depth: 118-178cm]

The clarity in presentation of this zone suffers unfortunately for those reasons explained for zone CWF/P/3 where close sampling across the minerogenic/biogenic boundary has been undertaken. The pollen assemblage changes are, however, reasonably clear. *Alnus* values have continued to increase to a peak in the uppermost levels of the zone at 77% of TLP. In contrast *Pinus* (*circa* 2%) and *Quercus* (<12%) values have fallen markedly. Coryloid values drop to *circa* 10% of TLP but record an anomalous peak in one level at 58%. Poaceae and Cyperaceae values both record an initial peak (17% and 9% respectively) before falling in the uppermost levels to *circa* 2%. Once again dwarf shrubs and aquatics are absent. Aquatics fall slightly from the previous zone as do the unidentified pollen grains. The indication from this assemblage is that although a mixed woodland remains in place within the valley of the Cree estuary alder has become the dominant taxon at the expense of pine and oak. It is also possible that with the change from estuarine sedimentation to peat growth that alder carr developed.

7.4.6 CWF/1: Pollen analysis (Figure 7.10a)

Altitude: 8.46-8.71m O.D. [Depth: 275-250cm]

Alnus dominates the assemblages with a range of 46% to 65% of TLP throughout. Similarly *Quercus* and Coryloid values (both <10%) remain stable across the carse/peat junction. The *Betula* curve is distinctive with low values at around 3% in the carse that increases sharply to *circa* 15% in the surface peats. These values indicate that an alder dominated carr with some mixed woodland was in place at this time. Poaceae values fall, albeit less markedly, across the sedimentary boundary from *circa* 25% to 0%. Spore values are low (<5% of TLP). The stability of the dominant taxon from this assemblage would indicate that the change from an estuarine depositional environment to peat formation was continuous. The Poaceae and *Betula* curves in contrast record sharp changes across the boundary between carse and surface peat. It is possible that these changes represent an hiatus in time. More probable, however, is that the shift from the grasslands of the estuarine saltings to the tree dominated peat mire was a rapid vegetational succession. One sample from the peat/carse boundary was subsequently sent for radiocarbon dating (3,810±70 ^{14}C years BP - Beta-83748) and full details are provided in Table 7.1.

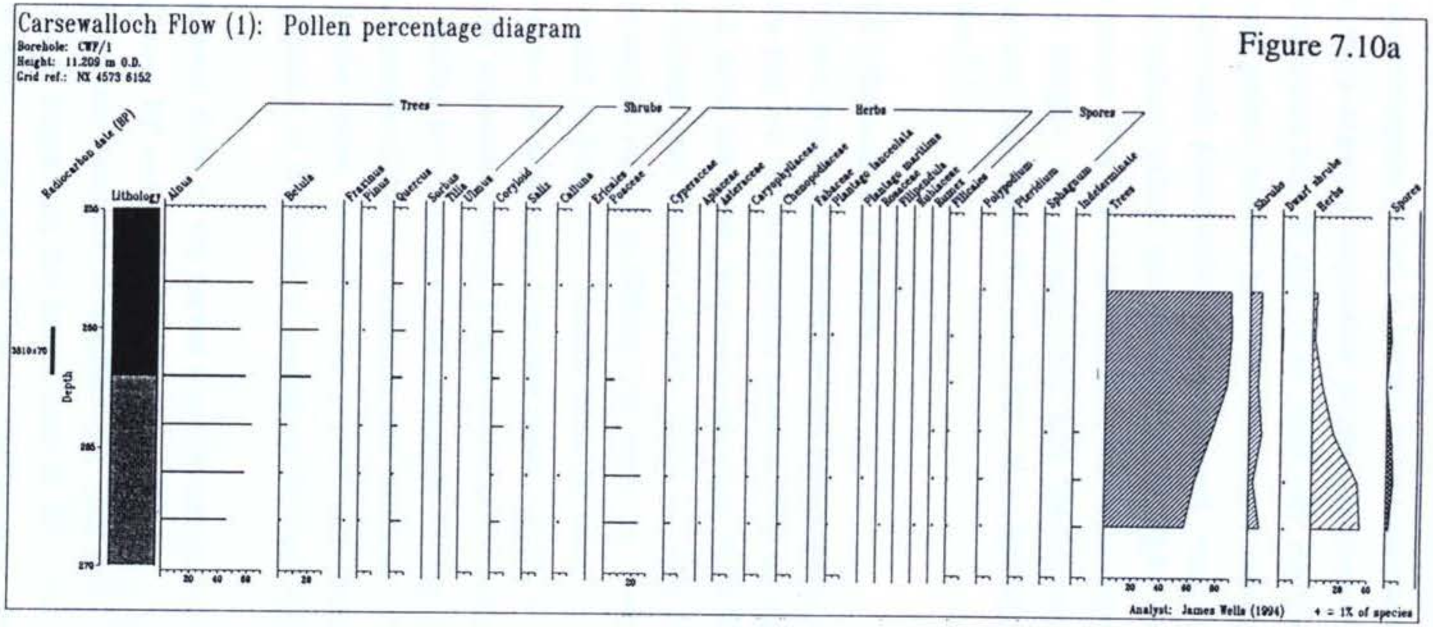


Figure 7.10a

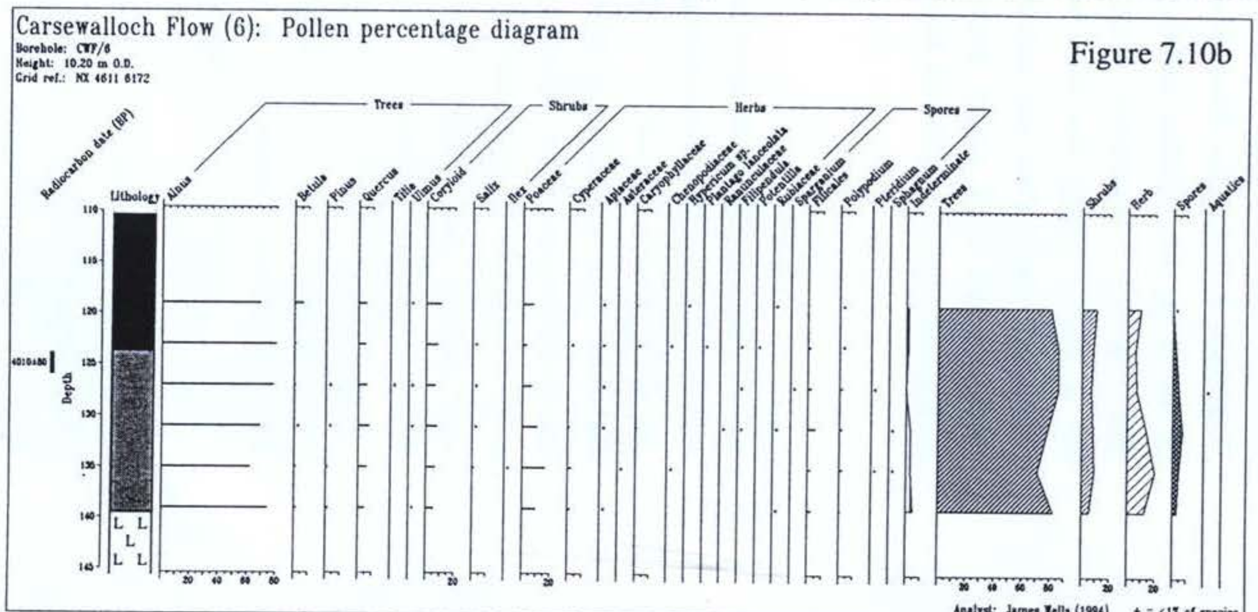


Figure 7.10b

7.4.7 CWF/6: Pollen analysis (Figure 7.10b)

Altitude: 8.75-9.10m O.D. [Depth: 145-110cm]

As with CWF/1 *Alnus* pollen dominates the assemblages with values ranging between 60% and 80% of TLP. The stability shown by this curve is also recorded in the other main taxa of *Quercus*, Coryloid and *Poaceae*. The proportion of *Alnus* pollen in the palaeoecological record is known to be over-represented resulting in the masking of the more regional vegetation picture (Janssen, 1959). Nonetheless, the indicated environment here is one of an alder carr dominating with some mixed woodland. *Pinus* pollen values fall into the peats which either reflects the reduction in preferential preservation or a regional vegetational adjustment. Filicales and *Polypodium* values are low (<10% of TLP) and relatively stable. There is no indication of a break in time between carse deposition and surface peat formation. One sample was subsequently sent for radiocarbon dating from the peat/carse boundary (4,010±80 ^{14}C years BP - Beta-83749) and details of this are provided in Table 7.1.

7.4.8 Summary of results

The clear sequence of thick (at least 8.5m) estuarine muds underlying compact buried peats that are in turn overlain by *circa* 10m of estuarine carse sediments and surface peats have not been previously recorded from the Cree Estuary. Shells from the lowermost part (*circa* -9.37m O.D.) of this sediment sequence were sent for radiocarbon dating (9,680±50 ^{14}C years BP - Beta-92209) full details of which are provided in Table 7.1. Results from the foraminifera and ostracod analyses record a sequence of sediments deposited under varying estuarine environments ranging from a high vegetated saltings terrace to sub-tidal mudflats. The diatom evidence indicates the marine provenance of the sediments but can not be used, in any way, to support the findings of the microfauna in this instance. The depth of sampled cores retrieved from the buried estuarine fine grained sediments at this location offered the only opportunity in this study to investigate in detail their microfossil content.

The *circa* 8.5m of the buried estuarine sediments were deposited between 9,680±50 ^{14}C years BP and 8,580±80 ^{14}C years BP. The microfauna indicate an inter-/sub-tidal mudflat environment throughout the majority of this sequence with the pollen evidence suggesting the valley sides to be covered in a hazel dominated woodland with birch, pine and willow - whether pine values are high due to preferential preservation is uncertain (see below). However, *circa* 1.8m below the buried peat layer the gradual change to a vegetated saltings environment is clear. This evidence reinforces the pollen results which do not indicate any lacunae in the transition between minerogenic and peat formation. The pollen assemblage throughout the buried peat layer gives perhaps the clearest indication of the vegetation in the region at this time. The grasses and sedges may well have dominated the recently exposed former saltings surface, however, a mixed woodland of hazel, birch, oak, elm, pine and willow was clearly evolving within the environs of the Cree estuary.

The *circa* 9.5m of carse overlying the buried peat and underlying the surface peats was deposited between 8,580±80 and *circa* 4,000 ^{14}C years BP (the later date is correlated from the nearby CWF/6 and CWF/1 carse/surface peat boundary radiocarbon dates). Similar to PAL/6 there are phases which record a distinct increase in tidal influence where the microfauna records the transition to and from inter-tidal mudflat conditions within a sequence of sediments deposited mainly in both low and high marsh environments. Here the diatom evidence identifies phasing within the sediment sequence but the indicated environmental changes are precisely opposite to the presumed actuality recorded by the microfauna.

The identification of an *Alnus* rise that coincides approximately with the uppermost of the inter-tidal mudflat phases (centre at *circa* 6.30m O.D.) may well date this environmental change to *circa* 7,600 ^{14}C years BP (correlated with the same event at Brighouse Bay - Chapter 5). Clearly, however, the assertion that the Alder rise phenomenon corresponds to Flandrian rising sea-levels (see Smith, 1984) is questionable for at this location relative sea-levels had been rising long before the Alder rise was initiated. More accurate may well be the suggestion that the Alder rise coincides with the culmination of maximum levels reached by the Flandrian sea of the Main Postglacial Transgression. Interestingly *Alnus* pollen grains are recorded occasionally throughout the core which may represent either long distance transport, reworking from sediments deposited during a previous (inter-glacial?) occupation of this tree or alternatively the presence of a local refuge in the region. Whatever the case, after the final regression of the sea the estuarine silts and clays are replaced by terrestrial peat development most probably in the form of an alder carr.

The correlation between peaks in the representation of *Pinus* pollen (zones CWF/P/2 and 5) and the phases of a saltings depositional environment (CWF/F/4 to 5 and CWF/F/7 to 8 respectively) has been recorded. As the depositional environment shifts to the low intertidal mudflats (F/1 to 3 and F/9 to 10) the *Pinus* pollen values are relatively low in each instance (P/1 and P/5 respectively). If these characteristics represent the differential preservation of saccate pollen in different intertidal environments the evidence presented here may go some way to developing the more general findings of similar research (Traverse and Ginsberg, 1966). It is possible, however, that the *Pinus* pollen fluctuations represent natural changes in regional pine populations.

7.5 Blairs Croft

7.5.1 BC/4/2: Foraminifera analysis (Table 7.8)

Of 21 samples prepared for foraminifera analysis thirteen were barren. In the remaining 8 samples 4 species were identified - species abundance per sample ranged from 1 to 67 tests. The paucity of foraminifera has meant that phases could not be identified (Table 7.8).

The marsh species *J. macrescens* is the most common foraminifera and is present in 7 samples. In only one of these (670-671cm; 3.03 to 3.02m O.D.) is this species accompanied by other foraminifera - one test of *M. fusca*. The other foraminifera bearing sample (550-551cm; 4.23 to 4.22m O.D.) contained the two calcareous, brackish, species *H. germanica* and *A. limnetes* both of which are commonly found on inter-tidal mudflats but also occasionally on the lower saltings terrace.

7.5.2 BC/4/2: Ostracod analysis

No ostracods were recorded from this core in any of the samples prepared.

7.5.3 BC/4/2: Pollen analysis (Figures 7.11, 7.12, 7.13, and 7.14)

The sampled core recovered from Blairs Croft (BC/4/2) contains a series of intercalating peat and carse layers all of which were investigated using pollen analysis to establish continuity of sedimentation across the lithological junctions. The results of these are presented below.

Altitude: 0.77-0.93m O.D. [Depth: 896-880cm] (Figure 7.11)

Cyperaceae is the dominant taxon with values ranging from 42% to a peak close to the peat/carse contact of 70%. In contrast both Coryloid and *Pinus* values dip from *circa* 20% to 10% of TLP across the sedimentary junction before recovering to *circa* 20%. *Betula*, *Quercus*, *Ulmus* and *Salix* record a low but consistent presence in all levels (<8% of TLP). Poaceae values similarly are low. *Alnus* pollen is absent from the assemblage. Spores are present in low numbers (<20% of TLP) of which the main taxa are Filicales and *Pteridium*. The results probably indicate that sedge species were locally abundant during the change from peat growth to estuarine sedimentation. Nearby, however, a pre-alder rise mixed woodland of hazel, pine, birch, oak, elm and

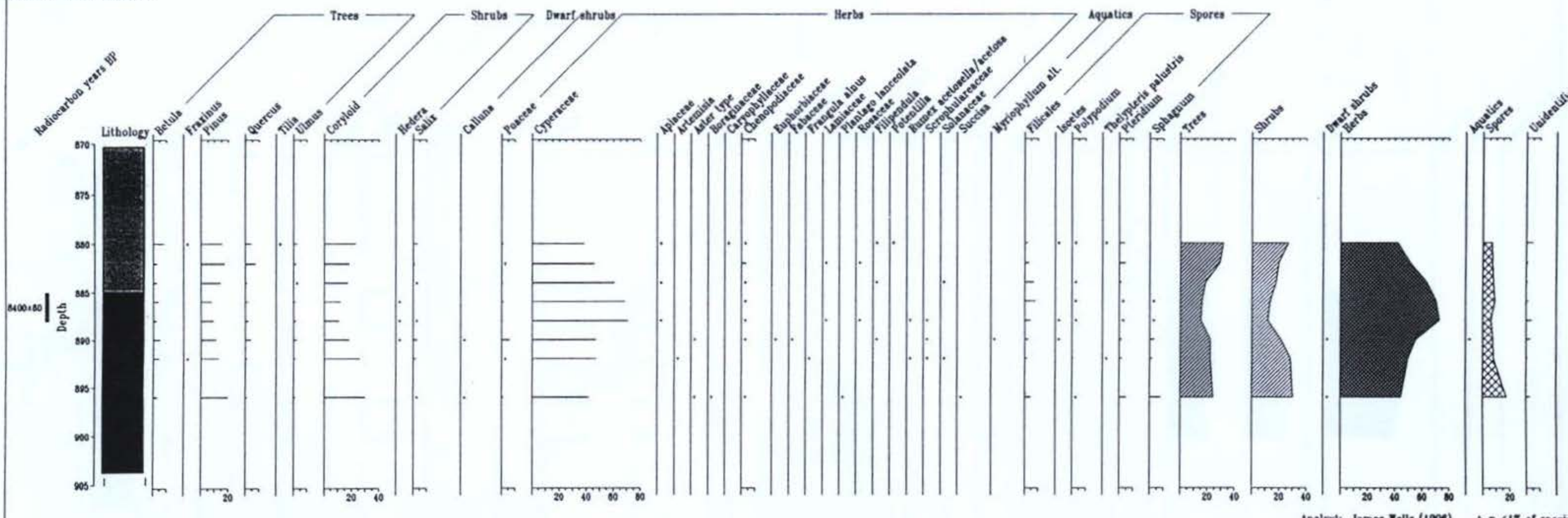
	830-831cm	750-751cm	670-671cm	550-551cm	510-511cm	470-471cm	450-451cm	295-296cm
J. macrescens	67	13	11	0	2	22	6	1
M. fusca	0	0	1	0	0	0	0	0
A. limnetes	0	0	0	3	0	0	0	0
H. germanica	0	0	0	8	0	0	0	0
Total number of individuals	67	13	12	11	2	22	6	1

Table 7.8 Showing the number of individual foraminifera per level (each is recorded in centimetres dpeth from ground surface) from core BC/T4/2. The following levels were barren of foraminifera: 330-331cm; 350-351cm; 370-371cm; 410-411cm; 430-431cm; 590-591cm; 630-631cm; 710-711cm; 790-791cm; 920-921cm; 940-941cm; 960-961cm; 965-966cm.

Blairs Croft (4/2): Percentage pollen diagram

Figure 7.11

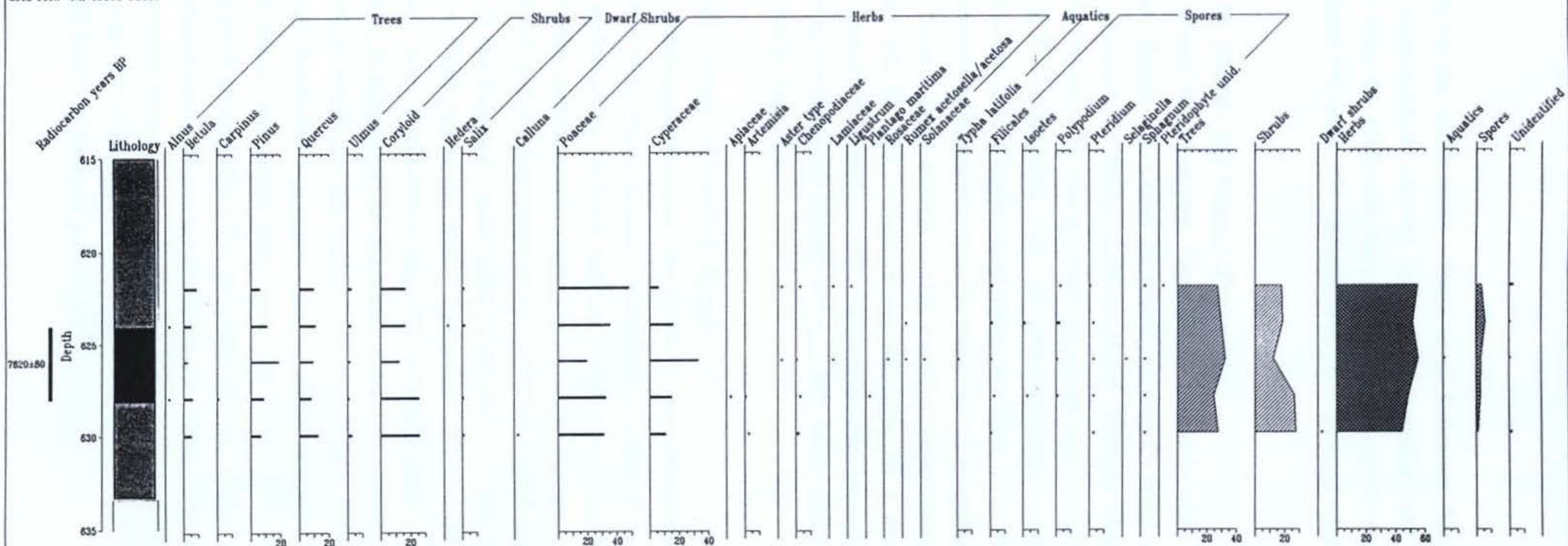
Borehole: BC/4/2
Height: 9.73m O.D.
Grid ref.: NX 46365 62228



Blairs Croft (4/2): Percentage Pollen Assemblage

Figure 7.12

Borehole: BC/4/2
Height: 9.73m O.D.
Grid ref.: NX 46365 62228



Analyst: James Wells (1996)   + = <1% of species

willow existed - possibly on the valley sides. There is no indication from this evidence of a break in sedimentation between buried peat formation and carse deposition. One sample from the peat/carse boundary was subsequently sent for radiocarbon dating (8,400±80 ^{14}C years BP - Beta-96324), full details of which are provided in Table 7.1.

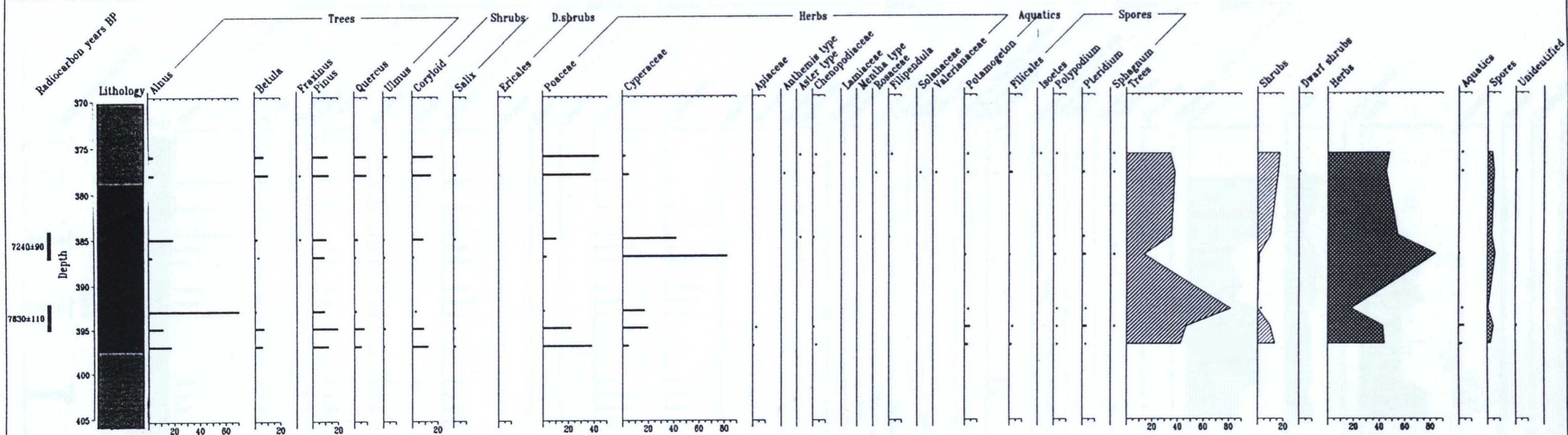
Altitude: 3.51-3.43m O.D. [Depth: 622-630cm] (Figure 7.12)
The pollen assemblage across the carse/peat intercalation fluctuates very little. Coryloid, *Pinus*, *Quercus*, *Betula* and *Ulmus* all record consistently high values throughout indicating the presence of a nearby mixed woodland. Poaceae values fall in the buried peat layer (to 17% of TLP) with a contrasting picture in the Cyperaceae curve which peaks (30% of TLP) at the same level. The presence of high numbers of grasses and sedges in the pollen record implies their dominance close to the sample location. *Alnus* pollen records an occasional presence which may be signaling the initiation of an alder rise. Spores are recorded in low but consistent values throughout ranging between 1% and 6% of TLP. There is no indication of a break in sedimentation across the carse/peat boundary. One sample from this boundary was subsequently sent for radiocarbon dating (7,820±80 ^{14}C years BP - Beta-100914), full details of which are provided in Table 7.1.

Altitude: 5.76-5.97m O.D. [Depth: 397-376cm] (Figure 7.13)
Contiguous sampling for pollen analysis across the carse/buried peat boundaries was hampered by the presence of wood within the peat. Nevertheless the pattern recorded is clear. Similar to the pollen across the lower boundaries (Figure 8.3) Cyperaceae values peak (83%) in the peats with Poaceae numbers dipping at the same point. The Coryloid, *Quercus* and *Betula* pollen curves (mean at *circa* 10%) all record similar, if less distinctive, patterns to the Poacaeae - each falling in the peats. *Pinus* (12% of TLP) and *Ulmus* (2% of TLP) values are stable throughout. Of chronological importance *Alnus* values have significantly increased although they fluctuate markedly (3% to 70% of TLP) throughout the assemblage recording a decline in the overlying carse. Spore values remain low and stable at *circa* 5% of TLP. The results indicate a sedge and grass dominated vegetation within a background of a mixed woodland comprised of hazel, oak, birch, alder, pine and elm. Although not unequivocal, mainly as a result of sampling difficulties, there does not appear to have been a break in sedimentation across the carse/peat boundaries. Two samples from the lower and upper sediment boundaries were subsequently sent for radiocarbon dating (7,830±110 ^{14}C years BP [Beta-100915] and 7,240±90 ^{14}C years BP [Beta-100916] respectively), full details of these are provided in Table 7.1.

Blairs Croft (4/2): Percentage Pollen Assemblage

Figure 7.13

Borehole: BC/4/2
Height: 9.73m O.D.
Grid ref.: NX 46365 62228

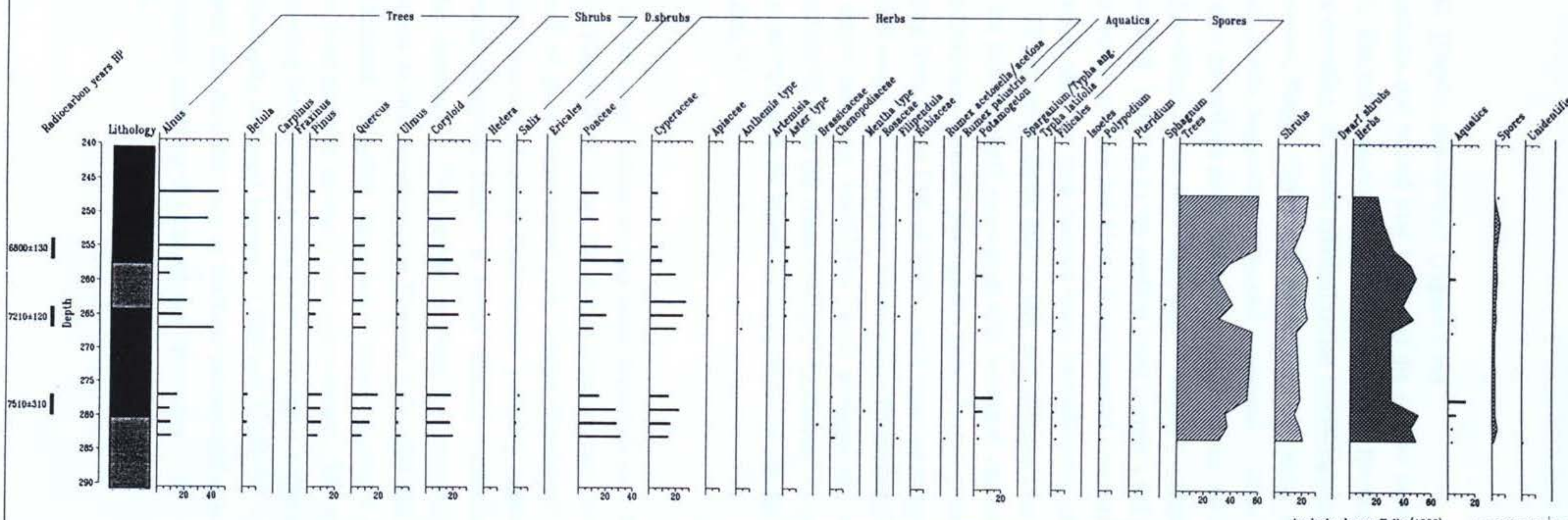


Analyst: James Wells (1996) + = <1% of species

Blairs Croft (4/2): Percentage Pollen Diagram

Figure 7.14

Borehole: BC/4/2
Height: 9.73m O.D.
Grid ref.: NX 46365 62228



Analyst: James Wells (1996) + = <1% of specie

Altitude: 6.90-7.26m O.D. [Depth: 283-247cm] (Figure 7.14)

This pollen assemblage includes one buried peat layer and the contact between the carse and the surface peats. The pollen assemblage across all contacts fluctuates little and no marked changes are recorded. A mixed arboreal pollen assemblage dominates with *Alnus*, Coryloid, *Quercus*, *Pinus*, *Ulmus* and *Betula* (in descending order of significance) present in all levels suggesting a mixed woodland. *Alnus* values dominate the assemblage into the surface peats indicating that the alder rise and, by inference, the formation of an alder carr are well underway. Poaceae and Cyperaceae values are commonly *circa* 20%; however in the surface peats numbers fall to 12% and 5% respectively. This would indicate that either environmental conditions were not suitable for these taxa or that the tree species were overwhelming the local vegetation at this time. Of the other herbs both *Aster* and Chenopodiaceae are regularly recorded which are taxa regularly associated with saltmarsh environments. Spore values remain low (<5%) but constant. The aquatic taxon *Potamogeton* is also recorded with values ranging from 0% to 13% of TLP. Once again there appears to be no indication of an hiatus across the carse/peat boundaries. Three samples from the lower, middle and upper sediment boundaries were subsequently sent for radiocarbon dating (7,510±310 ^{14}C years BP [Beta-100917], 7,210±120 ^{14}C years BP [Beta-100918] and 6,800±130 ^{14}C years BP [Beta-100919] respectively), full details of these are provided in Table 7.1.

7.5.4 Summary

The microfaunal content of the carse sediments that were deposited over the time period from 8,400±80 to 6,800±130 ^{14}C years BP at this location was poor - it is uncertain if this is a result of poor preservation (e.g. calcite dissolution) or low abundance. The occasional presence of marsh foraminifera probably indicates that the Blairs Croft area never deepened below a lower saltings environment of deposition throughout the sequence. The pollen analysis has shown that the intercalating peat/carse layers at this location (see Chapter 6 for full description) indicate no depositional lacunae. Whether these intercalations represent regional oscillations in relative sea level remains unclear from this evidence. The timing of the alder rise at this location has been marred by the anomalous dates of Beta-100914 and Beta-100915 but undoubtedly occurred between 7,800 and 7,200 ^{14}C years BP. This provides strong support that the alder rises in the Cree estuary and at Brighouse Bay were broadly synchronous justifying the use of this phenomenon as a suitable chronological marker here.

7.6 Carslae Cottage

7.6.1 CC/2: Foraminifera analysis (Figure 7.15; Table 7.9)

Foraminifera analysis on the sampled core taken from Carslae Cottage allowed the identification of five phases (Figure 7.15). The main characteristics and species associations of each phase are summarised in Table 7.9). Throughout the sequence foraminifera abundance is generally high with counts of over 300 tests possible in the majority of levels. Approximately sixty species have been identified although species diversity in any level does not exceed thirty. The uppermost *circa* 60cm of the sequence was not sampled due to disturbance by ploughing.

CC/F/1 -1.98 to -1.23m O.D. [Depth: 1000-1075cm]

This lowermost phase is comprised of only one level and its inclusion as a separate distinctive phase is tentative. The euryhaline *H. germanica* is the dominant species present - as it is in all levels of this assemblage. The brackish and brackish/marine *Ammonia* sp. and *Elphidium* sp. are all present in low numbers as are total values of marine (inner shelf) species. This assemblage is probably representative of a brackish low intertidal mudflat.

CC/F/2 -1.23 to 1.92m O.D. [Depth: 685-1000cm]

Haynesina germanica remains as the dominant species in all levels with *E. oceanensis* present in low but consistent numbers. The marine (inner shelf) *C. balkwilli* is also recorded in all but one level in this phase. The environmental interpretation of the poorly diverse assemblages in this phase is again one of a low intertidal mudflat probably under greater influence from the open marine waters of Wigtown Bay.

CC/F/3 1.92 to 4.47m O.D. [Depth: 430-685cm]

Values of *H. germanica* are variable but this species remains dominant. *Elphidium oceanensis* numbers fall so that by mid-phase this species is only occasionally recorded. A number of species including *Ammonia aberdoveyensis, A. limnetes*, *Ammonia batavus* and *E. excavatum* show increasing values toward the top of the phase. A peak mid-phase of *Anomalina* cf. *globulosa* is distinctive and appears to correlate with a brief peak in *J. macrescens*. Species diversity is, in general, high and rises to a maximum in the uppermost level of the phase. The synchronous rise of a number of species in this phase clearly reflects a changing depositional environment. The fluctuating values of marine (inner shelf) species may imply increasing salinity. However, the two marine species *A. batavus* and *A.* cf. *globulosa* are in the main responsible for these fluctuations of which the former is common to sandier estuarine

Figure 7.15 Carslae Cottage: Foraminifera

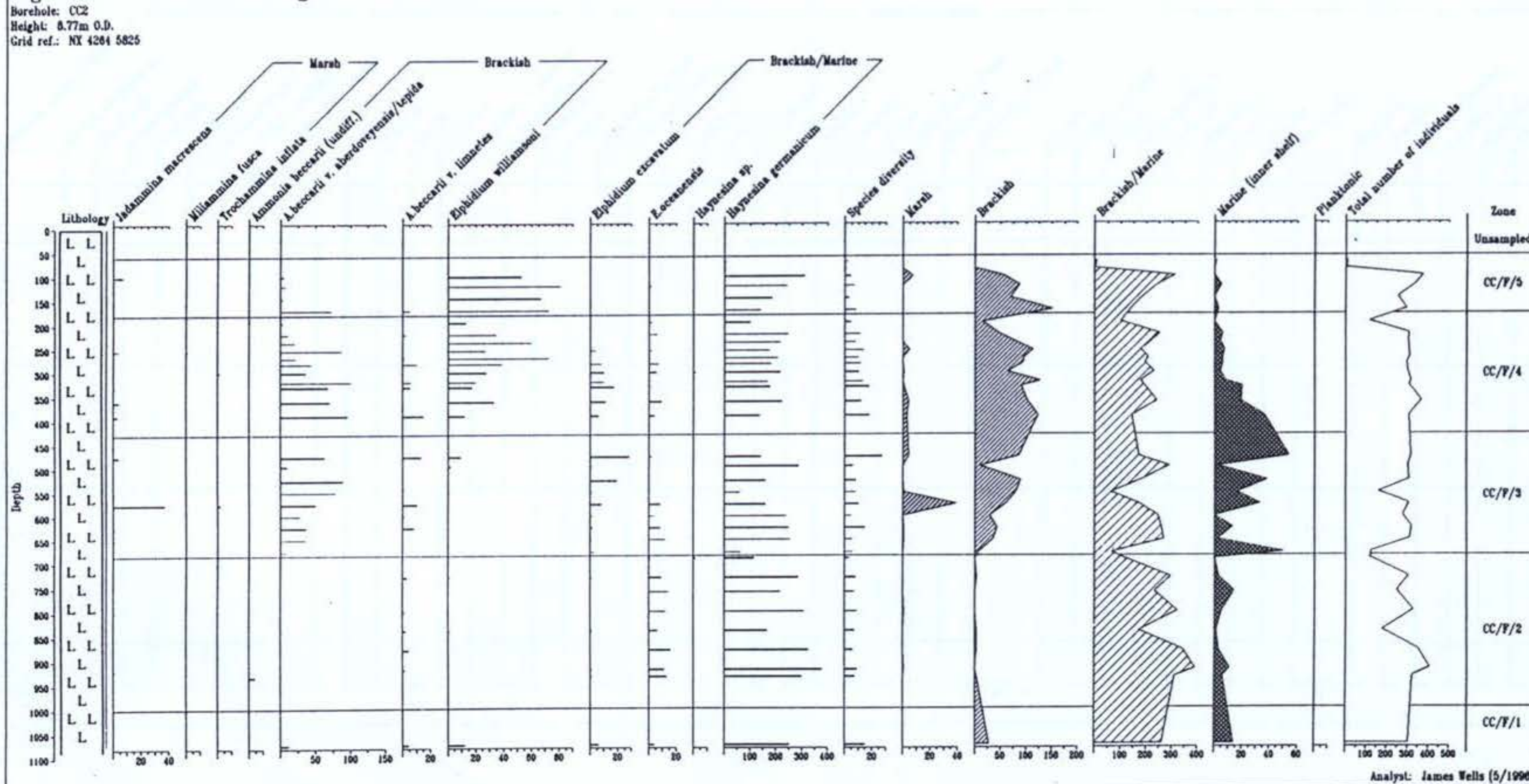
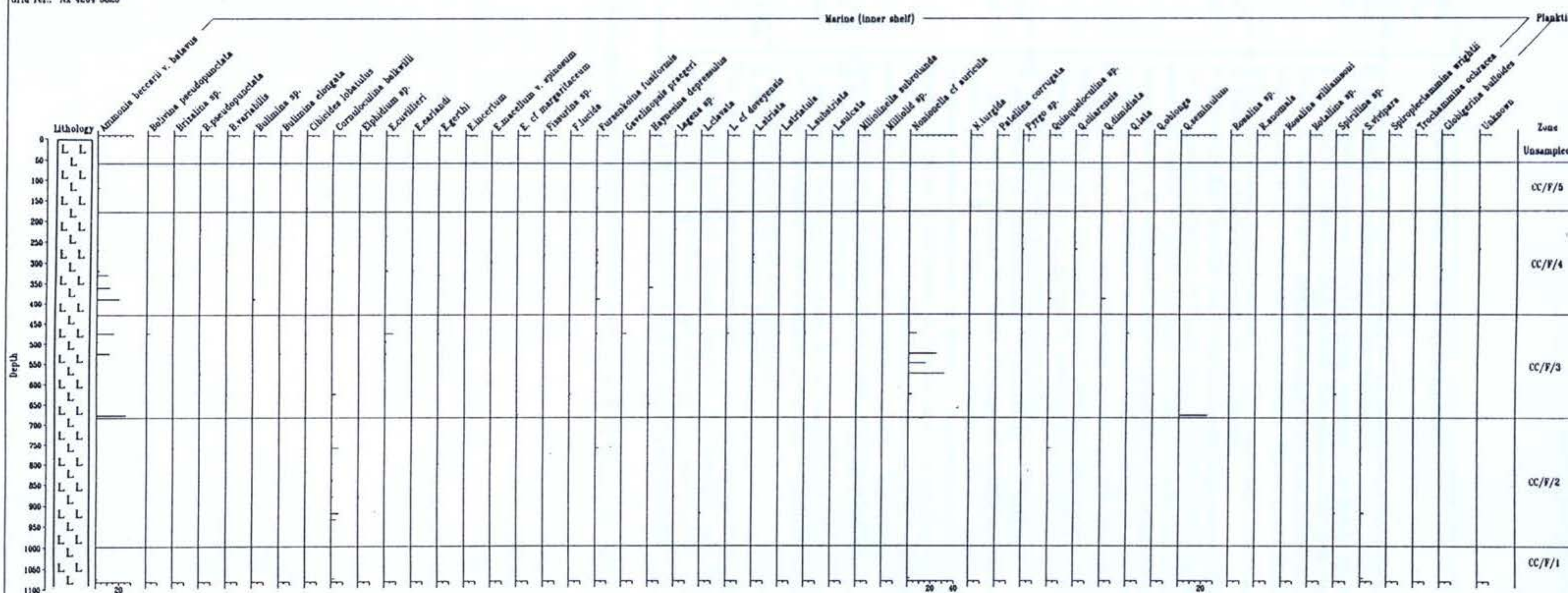


Figure 7.15 Carslae Cottage: Foraminifera (cont.)

Borehole: CC2
Height: 8.77m O.D.
Grid ref.: NX 4264 5825



Analyst: James Wells

CC2 Foram. Phases	Altitude (m O.D.) Depth (cm)	Main characteristics of foraminifera phase
CC/F/5	**8.17-6.97** 60-180	***H. germanica - E. williamsoni - A. aberdoveyensis*** *H. germanica* dominates the phase being abundant in all but the upper two levels. *E. williamsoni* is present in high numbers throughout excluding the uppermost two levels. *A. aberdoveyensis* numbers are high in the lowermost level of the phase before falling to low values for the remainder. Marine (inner shelf) species are rare.
CC/F/4	**6.97-4.47** 180-430	***H. germanica - A. aberdoveyensis - E. williamsoni*** *H. germanica* dominates the phase with consistantly high numbers throughout. *A. aberdoveyensis* is present in with high values for the first half of the phase before a steady fall toward the upper boundary. *A. limnetes* records a similar pattern but in lower numbers. *E. williamsoni* and, to a lesser degree, *E. excavatum* both show an increasing trend in numbers to mid-phase before falling again in the uppermost levels. *E. oceanensis* values fluctuate in low numbers throughout the phase. Marine (inner shelf) species diversity is relatively high but in low numbers. Of these only *A. batavus* is recorded in numbers and this shows a fall in values to eventually record only a presence by mid-phase.
CC/F/3	**4.47-1.92** 430-685	***H. germanica - A. aberdoveyensis - Elphidium* sp. - *Ammonia* sp.** *H. germanica* dominates the phase although is occasionally recorded in low concentrations. *A. aberdoveyensis*, *A. limnetes* and *E. excavatum* all record increasing numbers throughout the phase. *E. oceanensis* shows falling numbers to record low values by mid-phase. *A. batavus* records a high value in the lowermost level of the phase after which it dissappears before returning by mid-phase where it increases in values toward the uppermost levels. The marine *Nonionella* cf. *auricula* is recorded in numbers in the middle section of the phase.
CC/F/2	**1.92 to -1.23** 685-1000	***H. germanica - E. oceanensis*** *H. germanica* dominates this phase. *E. excavatum* is also recorded consistantly in low values throughout. Of the marine species only *C. balkwilli* records a regular presence. Species diversity is relatively low.
CC/F/1	**-1.23 to -1.98** 1000-1075	***H. germanica - Ammonia* sp. - *Elphidium* sp.** This phase is included tentatively as it is based on only one level. *H. germanica* remains the dominant species, however, the brackish and brackish/marine *Ammonia* sp. and *Elphidium* sp. are all recorded in low numbers. Of the marine species *A. batavus*, *C. balkwilli* and *N.* cf. *auricula* are all present.

Table 7.9 Main characteristics of foraminifera phases in core CC2, Carslae Cottage.

environments. The changes outlined here probably reflect that there was a transition to a low intertidal or even subtidal mudflat environment where salinity fluctuations are higher and numbers of allochthonous, marine (inner shelf) species are more common.

CC/F/4 4.47 to 6.97m O.D. [Depth: 180-430cm]
Haynesina germanica continues to dominate throughout this phase. Values of *E. aberdoveyensis*, *A. limnetes*, *E. excavatum* and *A. batavus* all fall throughout the phase to eventually record a low presence or complete absence. *Elphidium williamsoni* increases sharply to a peak mid-phase before falling as quickly to low numbers by the top of the zone. There is also a return in low but consistent numbers of *E. oceanensis*. This association of species probably indicates a low intertidal mudflat environment which remains under an open marine influence.

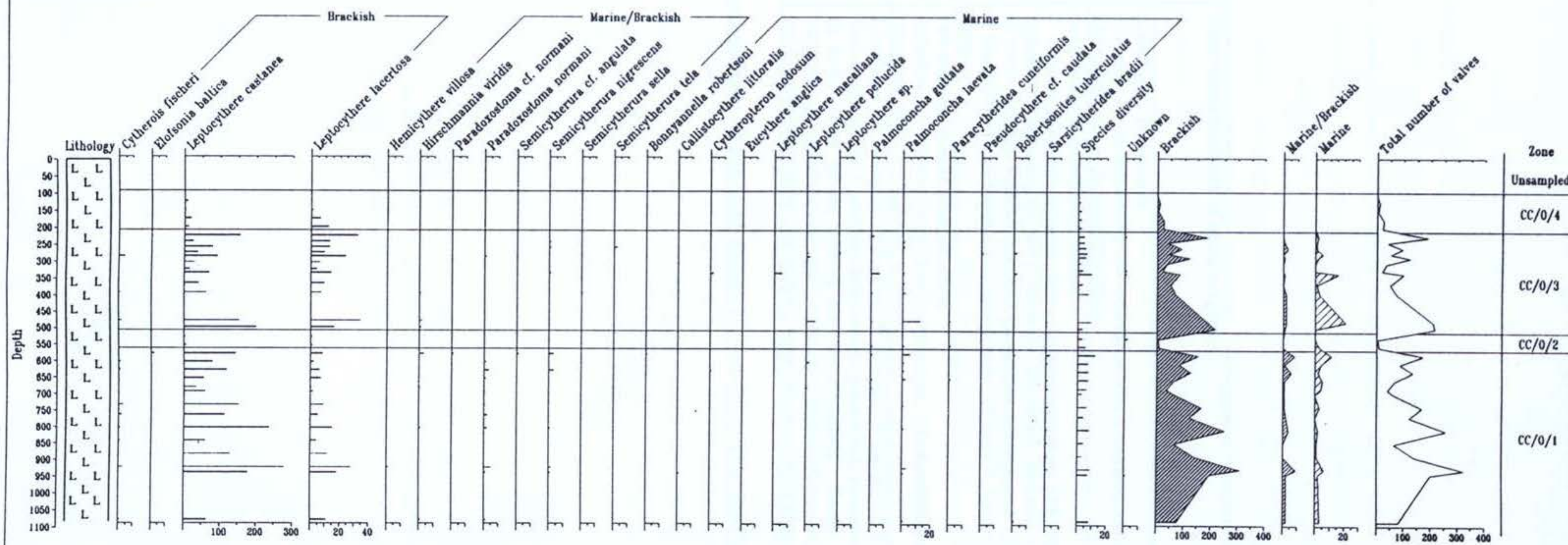
CC/F/5 6.97 to 8.17m O.D. [Depth: 60-180cm]
The two species *H. germanica* and, to a lesser degree, *E. williamsoni* clearly dominate this phase. *Ammonia* sp. are occasionally present but generally in low numbers. Marine (inner shelf) species are recorded infrequently in low numbers. The marsh species remain poorly represented. The low diversity and unchanging assemblage probably reflects an increased stability in environment of the intertidal mudflat identified from the previous phase.

7.6.2 CC/2: Ostracod analysis (Figure 7.16; Table 7.10)

Ostracod analysis on the sampled core taken from Carslae Cottage allowed the identification of four phases (Figure 7.16). The main characteristics and species associations are summarised in Table 7.10. Throughout the sequence ostracod recovery is relatively good although abundances were in general less than for foraminifera with only one level exceeding 300 valves. Twenty five species were identified. As for the foraminifera analysis the uppermost disturbed sediments were not sampled for ostracods.

Figure 7.16 Carslae Cottage: Ostracods

Borehole: CC2
Height: 8.77m O.D.
Grid ref.: NX 4264 5825



Analyst: James Wells (5/1996)

CC2 Ostracod Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of ostracod phase
CC/O/4	**7.87-6.72** 90-205	***L. castanea - L. lacertosa*** This phase is characterised by low numbers of both *L. castanea* and *L. lacertosa* which dissappear in the uppermost levels.
CC/O/3	**6.72-3.72** 205-505	***L. castanea - L. lacertosa - P. laevata*** *L. castanea* dominates although values fluctuate throughout with concentrations highest at the beginning and end of the phase. Similarly *L. lacertosa* is common in all levels recording a similar pattern of fluctuations to *L. castanea*. The diversity of marine/brackish and marine is relatively high. Of these *P. laevata* is the most common.
CC/O/2	**3.72-3.17** 505-560	**Low concentration of ostracod valves** All species are recorded in very low concentrations. The assemblage composition is however similar to phase O/3.
CC/O/1	**3.17 to -1.98** 560-1080	***L. castanea - L. lacertosa - C. fischeri - P. normani - P. laevata - S. bradii*** The brackish species *L. castanea* dominates the phase with *L. lacertosa* common in all levels - both species fluctuate markedly throughout. Faunal diversity is relatively high and of the other species present *C. fischeri*, *P. normani*, *P. laevata* and *S. bradii* are the most common being recorded in most levels of this phase.

Table 7.10 Main characteristics of ostracod phases in core CC/2, Carslae Cottage

CC/O/1 -1.98 to 3.17m O.D. [Depth: 560-1080cm]
This lowermost phase covers approximately 5 metres of the sequence. *Leptocythere castanea*, like *H. germanica* in the foraminifera, dominates the phase as it does the rest of the assemblage. The only other species represented in all levels is *L. lacertosa* but in much lower numbers compared to the former species. Other ostracod species that record a presence regularly within this phase are the brackish *C. fischeri*, the marine/brackish *P. normani* and the marine *P. laevata* and *Sarscytheridea bradii*. It is probable that this assemblage represents a low intertidal mudflat in the main part of the estuary where salinities are very brackish but not fully marine.

CC/O/2 3.17 to 3.72m O.D. [Depth: 505-560cm]
Very low numbers of ostracods characterise this phase with *L. castanea* and *L. lacertosa* recording a low presence and in the lowermost half of the phase three marine species also present. This limited evidence does not allow an accurate environmental interpretation.

CC/O/3 3.72 to 6.72m O.D. [Depth: 205-505cm]
Leptocythere castanea and *L. lacertosa* are the dominant species in this phase. Numbers of marine/brackish and marine species are high in the lowermost half of the phase but fall toward the upper limits. Of these the main species are *P. laevata*, *P. guttata*, *Leptocythere pellucida* and *Cytherois fischeri*. This assemblage probably reflects a depositional environment of a very brackish subtidal or low intertidal mudflat in the lower half of the phase possibly changing to a brackish intertidal mudflat in the upper half.

CC/O/4 6.72 to 7.87m O.D. [Depth: 90-205cm]
The uppermost phase is characterised by low values of *L. castanea* and falling numbers of *L. lacertosa*. No other species are present. These changes, if not resulting from poor preservation, probably indicate the increasing distance of this location from the main estuary. The environment of deposition is probably that of a high intertidal mudflat.

7.6.3 Summary of results

The Carslae Cottage location is the most distant from the River Cree channel although due to its southerly position it is the closest of all the sampled boreholes to the open marine waters of Wigtown Bay. No surface peat nor buried peat layers were recorded in the stratigraphy down to at least *circa* -2m O.D. and no radiocarbon dates have been obtained from this core. The close proximity of this site to Carsegowan Moss where surface peat still exists has allowed a tentative correlation between the dates of the surface peat/carse junction (e.g. CGM/4 and CGM/8 index points - see section 7.7 below) and the top of the CC/2 core. These may indicate a *circa* 4,000 ^{14}C years BP cessation of carse deposition in this area at *circa* 9m O.D..

The microfauna of CC/2 core is generally more abundant than in the previous boreholes. In the lowermost level of the sequence there is evidence for an intertidal mudflat which may indicate that shallower conditions were present lower in the (unrecovered) sedimentary sequence. Up to *circa* 2m O.D. the microfauna probably records a low intertidal mudflat depositional environment prior to an increase in marine conditions by *circa* 5m O.D. - the environment of deposition probably remained as a very low intertidal mudflat but closer to the open marine waters of Wigtown Bay. Throughout the remainder of the sequence the evidence indicates either a shallowing to a low and then back to a high intertidal mudflat or a decrease in the influence of marine waters.

Undoubtedly the absence of material for radiocarbon dating in the core makes a full interpretation difficult as does the lack of recovery of sediments from lower in the sedimentary sequence.

7.7 Carsegowan Moss/Moss of Cree

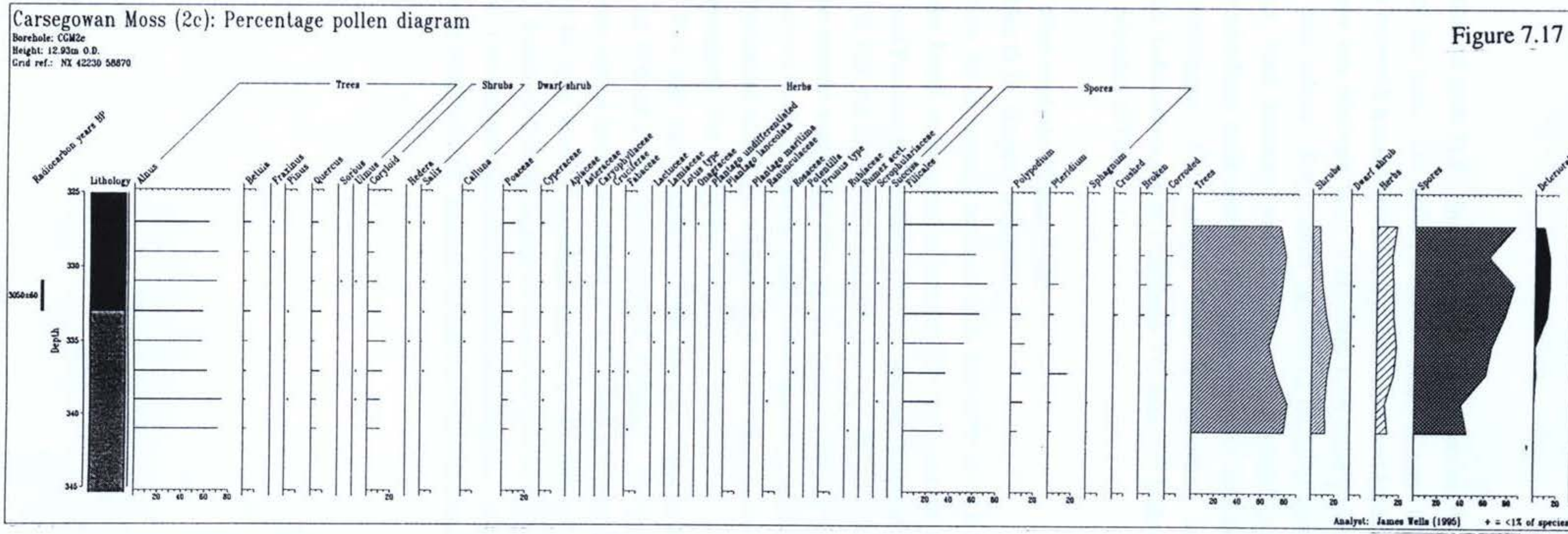
7.7.1 Introduction

Cores from five surface peat/carse contacts were sampled from locations CGM/2c, CGM/4, CGM/8, MOC/1 and MOC/16 for pollen analysis and radiocarbon dating. Where possible each sample was selected where the transition from minerogenic to organic sediments appeared most gradual. The main characteristics of each pollen assemblage is described briefly below.

7.7.2 CGM/2c: Pollen analysis (Figure 7.17)

Altitude: 9.48-9.68m O.D. [Depth: 345-325cm]

By far the most dominant taxon of this assemblage is *Alnus* which ranges between *circa* 55% and *circa* 73% of TLP. Of the other tree taxa present only *Betula* and *Quercus* are recorded in all levels at <10%. Coryloid values are low (*circa* 10%), similar to those for Poaceae, but consistent. Herb diversity is generally good but no species indicative of salt marsh conditions (e.g. *Plantago maritima*, *Aster* type) records a regular presence. Spore values, particularly Filicales, *Polypodium* and *Pteridium*, are recorded in high values with an increasing upward trend through the


Carsegowan Moss (2c): Percentage pollen diagram
Borehole: CGM2c
Height: 12.93m O.D.
Grid ref.: NX 42230 58870
Figure 7.17
Trees
Shrubs
Dwarf shrub
Herbs
Spores
Radiocarbon years BP
Lithology
Depth
3050±60
Alnus
Betula
Fraxinus
Pinus
Quercus
Sorbus
Ulmus
Coryloid
Hedera
Salix
Calluna
Poaceae
Cyperaceae
Apiaceae
Asteraceae
Caryophyllaceae
Cruciferae
Fabaceae
Lactuceae
Lamiaceae
Lotus type
Onagraceae
Plantago undifferentiated
Plantago lanceolata
Plantago maritima
Ranunculaceae
Rosaceae
Potentilla
Prunus type
Rubiaceae
Rumex acet.
Scrophulariaceae
Succisa
Filicales
Polypodium
Pteridium
Sphagnum
Crushed
Broken
Corroded
Trees
Shrubs
Dwarf shrub
Herbs
Spores
Deteriorated
Analyst: James Wells (1995)
+ = <1% of species

assemblage from 40% to 80% TLP. Indeterminate grains increase markedly in the upper (peat) half of the core. The pollen evidence here indicates an environment dominated by alder carr with a mixed woodland of birch, oak and hazel nearby. That the woodland canopy was relatively open is indicated with some grasses, good herb diversity and high fern values. The marked increase of the latter species probably reflects the change from estuarine sedimentation to terrestrial peat formation indicating a locally wet/damp environment. No hiatus in sedimentation is indicated by the pollen assemblages. One sample from the peat/carse boundary was subsequently sent for radiocarbon dating (3,050±60 ^{14}C years BP [Beta-84189]), full details of these are provided in Table 7.1.

7.7.3 CGM/4: Pollen analysis (Figure 7.18)

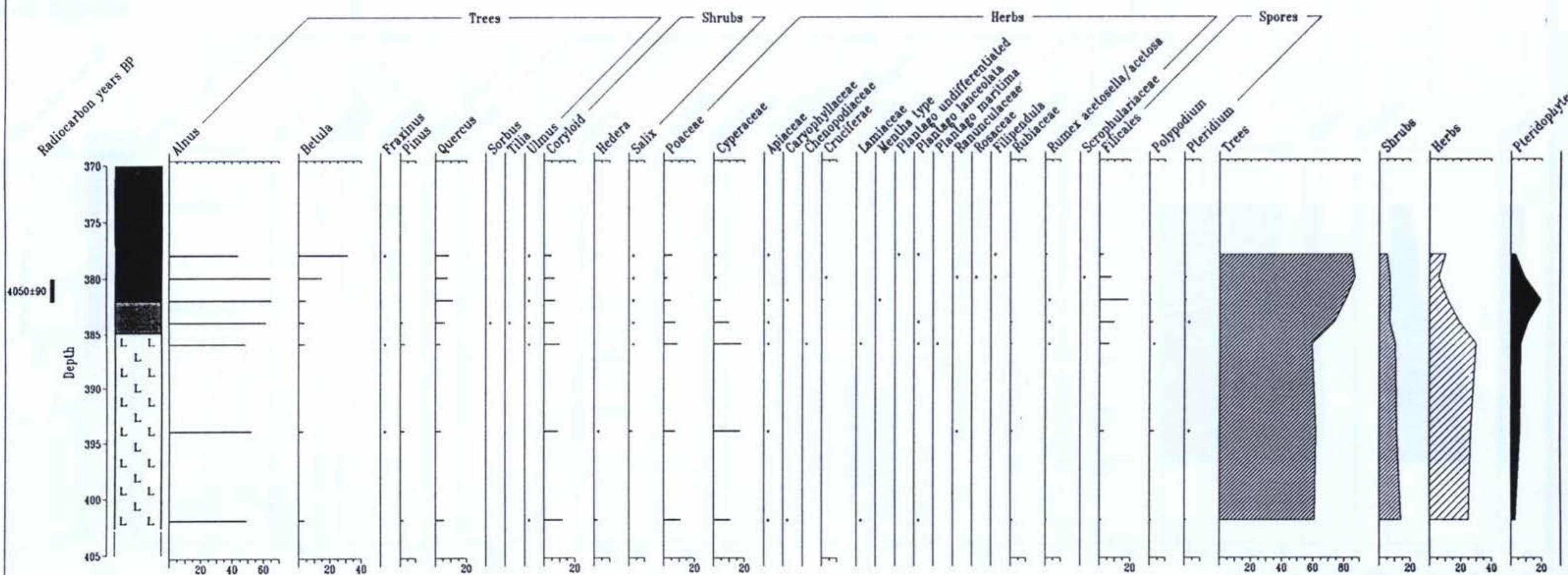
Altitude: 9.00-9.35m O.D. [Depth: 405-370cm]

Alnus is the dominant taxon ranging between 45% and 65% of TLP but no sharp changes in values are found at the junction between the carse and the surface peats. *Quercus*, Coryloid and Poaceae all similarly show no marked change in values (range approximately 5-12% TLP for all taxa) throughout the core. *Betula* values across the carse/peat transition remain constantly low at 5% before showing an increase in numbers in the upper two levels of the sequence (both in peat) to a peak at 30% by the top of the core. Cyperaceae values are initially high in the carse (*circa* 15%) before falling steadily throughout the transition to peat ending at 2% of TLP in the uppermost level. Few salt marsh indicators are present. Numbers of Filicales increase to a peak of 17% of TLP at the carse/peat boundary. The pollen evidence indicates an alder carr with a mixed woodland of oak, hazel and increasing numbers of birch surrounded by open areas of grassland and ferns. Evidence for an hiatus is poor and a gradual transition from estuarine to terrestrial conditions is indicated by the pollen spectrum. One sample from the peat/carse boundary was subsequently sent for radiocarbon dating (4,050±90 ^{14}C years BP [Beta-83746]), full details of these are provided in Table 7.1.

Carsegowan Moss (4): Percentage pollen diagram

Figure 7.18

Borehole: CGM4
Height: 13.05m O.D.
Grid ref.: NX 4239 5890

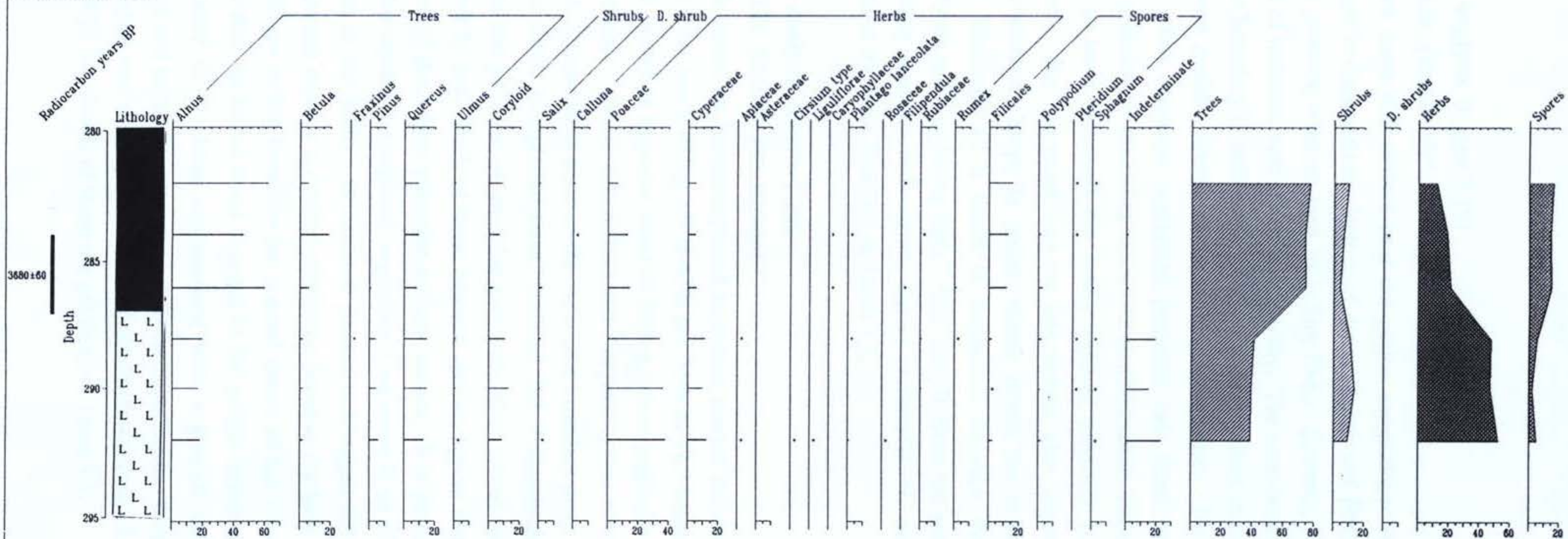


Analyst: James Wells (1995) + = <1% of species

Carsegowan Moss (8): Percentage pollen diagram

Figure 7.19

Borehole: CGM/8
Height: 11.84m O.D.
Grid ref.: NX 4302 5898



Analyst: James Wells (1994) + = <1% of species

7.7.4 **CGM/8: Pollen analysis** (Figure 7.19)

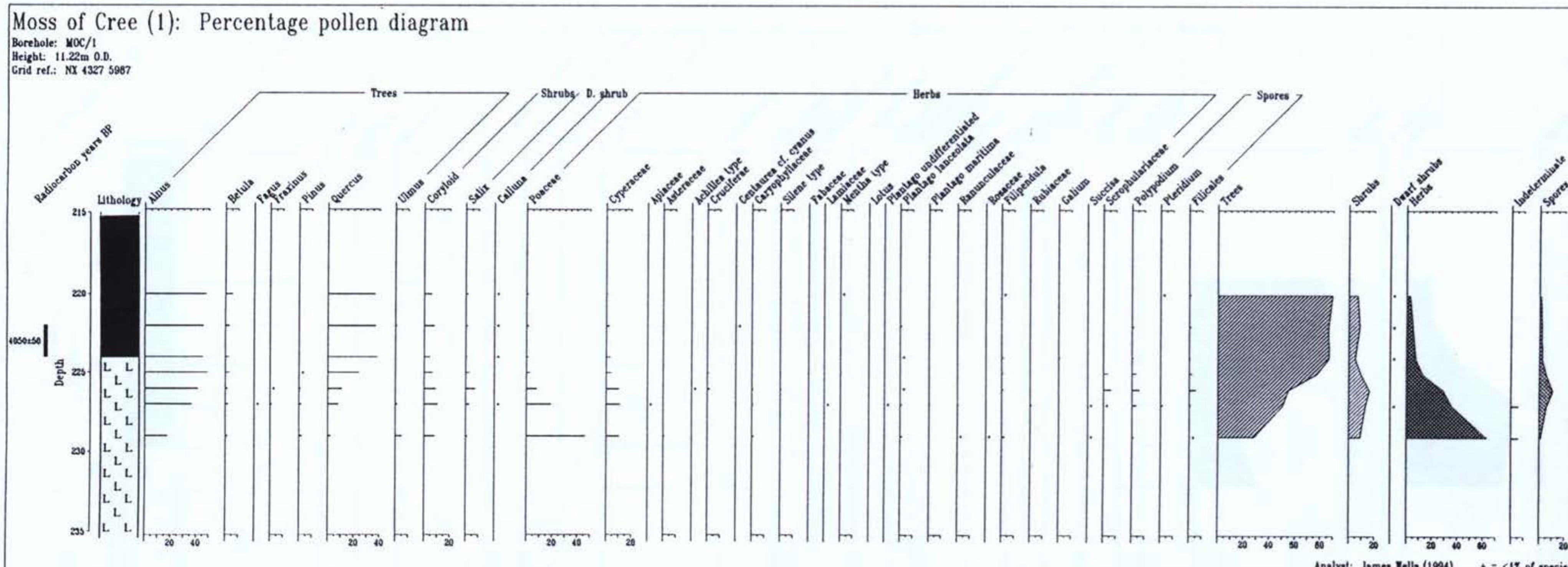
Altitude: 8.89-9.04m O.D. [Depth: 295-280cm]

At the boundary between carse and surface peat the pollen assemblages record a number of marked changes in composition. Values of *Alnus*, *Betula* and Filicales all increase in value at this junction whereas taxa including *Pinus*, *Quercus*, Poaceae, Cyperaceae and numbers of indeterminate grains fall abruptly. The consistency of the values either side of this boundary is noticeable. Only Coryloid values record little evidence for this otherwise marked change in the pollen assemblages. The pollen evidence indicates that while estuarine conditions persisted oak, hazel and pine woodlands were present probably on the valley sides. As peat formation was initiated alder and birch appear to have colonised the newly exposed estuarine surface - probably as an alder carr. The wet conditions on this surface also allowed fern species to thrive. The marked change in pollen values across the sedimentary boundary indicates the likelihood of a break in deposition between the carse sediments and the overlying peats as being high. One sample from the peat/carse boundary was subsequently sent for radiocarbon dating (3,680±60 ^{14}C years BP [Beta-83747]), full details of these are provided in Table 7.1.

7.7.5 **MOC/1: Pollen analysis** (Figure 7.20)

Altitude: 8.87-9.07m O.D. [Depth: 235-215cm]

Alnus and *Quercus* both record an increasing trend in values toward the carse/peat boundary at which point there is a leveling off at 45% and 33% of TLP respectively. Poaceae and Cyperaceae record an opposite trend of falling values gradually toward the junction of the sediments. *Betula* (*circa* 5%) and Coryloid (*circa* 8%) values remain stable throughout. Immediately prior to the carse/peat boundary there are low but distinctive peaks in *Salix*, Scrophulariaceae, Filicales and *Polypodium*. The pollen evidence indicates the presence of an alder carr with other mixed woodland species present dominated by oak. Both of these arboreal species appear to respond positively to the exposure of the former estuarine saltings surface. It is possible that the birch and hazel pollen represent a regional vegetational signature if an alder carr was present in the centre of the valley. In contrast, grasses and sedges fall as peat formation prevails. Although there is a marked difference between the base and the top of the pollen assemblage in this borehole the gradual nature of the transition is noticeable. Thus rather than an hiatus these changes in the pollen record probably reflect the changing nature of the local environment with a gradual shift from estuarine saltings (grasses and sedges) to terrestrial alder carr conditions. One sample from the peat/carse boundary was subsequently sent for radiocarbon dating (4,050±50 ^{14}C years BP [Beta-83750]), full details of these are provided in Table 7.1.

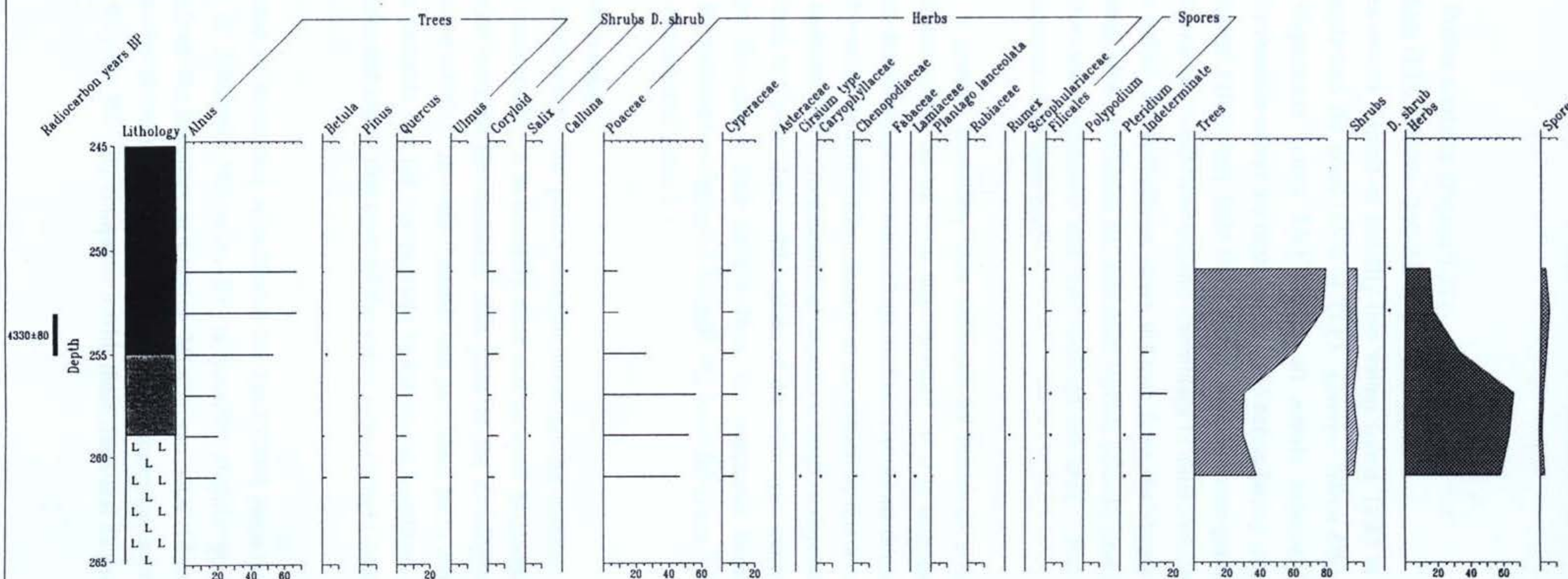


Moss of Cree (1): Percentage pollen diagram
Borehole: MOC/1
Height: 11.22m O.D.
Grid ref.: NX 4327 5987
Trees
Shrubs
D. shrub
Herbs
Spores
Radiocarbon years BP
Lithology
Depth
4050±50
Alnus
Betula
Fagus
Fraxinus
Pinus
Quercus
Ulmus
Coryloid
Salix
Calluna
Poaceae
Cyperaceae
Apiaceae
Asteraceae
Achillea type
Cruciferae
Centaurea cf. cyanus
Caryophyllaceae
Silene type
Fabaceae
Lamiaceae
Mentha type
Lotus
Plantago undifferentiated
Plantago lanceolata
Plantago maritima
Ranunculaceae
Rosaceae
Filipendula
Rubiaceae
Galium
Succisa
Scrophulariaceae
Polypodium
Pteridium
Filicales
Trees
Shrubs
Dwarf shrubs
Herbs
Indeterminate
Spores
215
220
225
230
235
Analyst: James Wells (1994)
+ = <1% of species

Moss of Cree (16): Percentage pollen diagram

Figure 7.21

Borehole: MOC/16
Height: 10.76m O.D.
Grid ref.: NX 4474 6003



Analyst: James Wells (1994) + = <1% of species

7.7.6 MOC/16: Pollen analysis (Figure 7.21)

Altitude: 8.11-8.31m O.D. [Depth: 265-245cm]

Alnus pollen values record a trend of initially low values (*circa* 18%) in the carse which increase sharply into the peats (65% of TLP). *Quercus* (*circa* 8%), Coryloid (*circa* 5%) and Cyperaceae (*circa* 8%) values all remain relatively constant throughout. Initially Poaceae values are high (*circa* 50%) before falling into the peats to 10% of TLP. Spores values vary little throughout. Indeterminate grains increase toward the top of the carse. A mixed woodland assemblage of alder, oak and hazel is indicated from the pollen but probably at some distance from the sample location. Grasses initially must have dominated the estuarine surface prior to peat formation when it appears that alder colonised and overwhelmed the area. This probably indicates the development of an alder carr.

The evidence for a gradual transition from estuarine to terrestrial conditions is somewhat mixed in the pollen record from this borehole. If it is accepted that the change from a grass-dominated pollen assemblage to that of an *Alnus* dominated one is a reflection of the actual rapidity of the change in vegetation at this location then there is no reason to assume that this assemblage records a break in deposition at the junction between carse and peat. The stable values of the other taxa would certainly indicate this to be the case. One sample from the peat/carse boundary was subsequently sent for radiocarbon dating (4,330±80 ^{14}C years BP [Beta-83751]), full details of these are provided in Table 7.1.

7.7.7 Summary of results

The assemblages recorded by the pollen analysis from all the surface peat/carse boundaries a very comparable. It is certainly clear that an open grassland and herb dominated vegetation covered the estuarine silts prior to the development of an extensive alder carr on which ferns were common and occasional birch and oak trees could thrive. It is probable that the composition of the mixed woodland (including oak, birch, pine, alder and hazel) that covered the valley sides changed little over this period.

Evidence for lacunae in deposition is indicated for the CGM/8 boundary and the radiocarbon date of 3,680±60 ^{14}C years BP is possibly slightly young. The radiocarbon dates from the boundary at CGM/4, MOC/1 and MOC/16 indicate the change from carse deposition to peat formation occurred sometime between *circa* 4,300 and 4,000 ^{14}C years BP. By comparison with these dates and its geographical location the date of 3,050±60 ^{14}C years BP for the boundary at CGM/2c is considered here to be anomalously young - the reasons for which are unknown.

7.8 Carse of Clary

7.8.1 COC/2: Foraminifera analysis (Figure 7.22; Table 7.11)

Foraminifera analysis on the sampled core taken from Carse of Clary has allowed the identification of five distinctive phases (Figure 7.22). The main characteristics and species associations are summarised in Table 7.11. Throughout the sequence foraminifera abundance was highly variable with counts of over 300 tests possible in some levels but in general less than this number was achieved. Thirty two species have been identified. The buried peat deposit was not sampled for foraminifera nor was the upper 70cm of carse which had been affected by modern farming.

COC2/F/1 2.43 to 4.63m O.D. [Depth: 465-685cm]

This lowermost phase immediately overlies the buried peat deposits. *Jadammina macrescens* and *A. limnetes* are both present in low but consistent values throughout the phase. The occasional test of *H. germanica* is also recorded in most levels. Few other species are recorded (species diversity is at *circa* 5) although the two agglutinating species of *M. fusca* and *T. inflata* both record a presence. This evidence indicates that this phase was deposited in a lower saltings environment.

COC2/F/2 4.63 to 5.63m O.D. [Depth: 365-465cm]

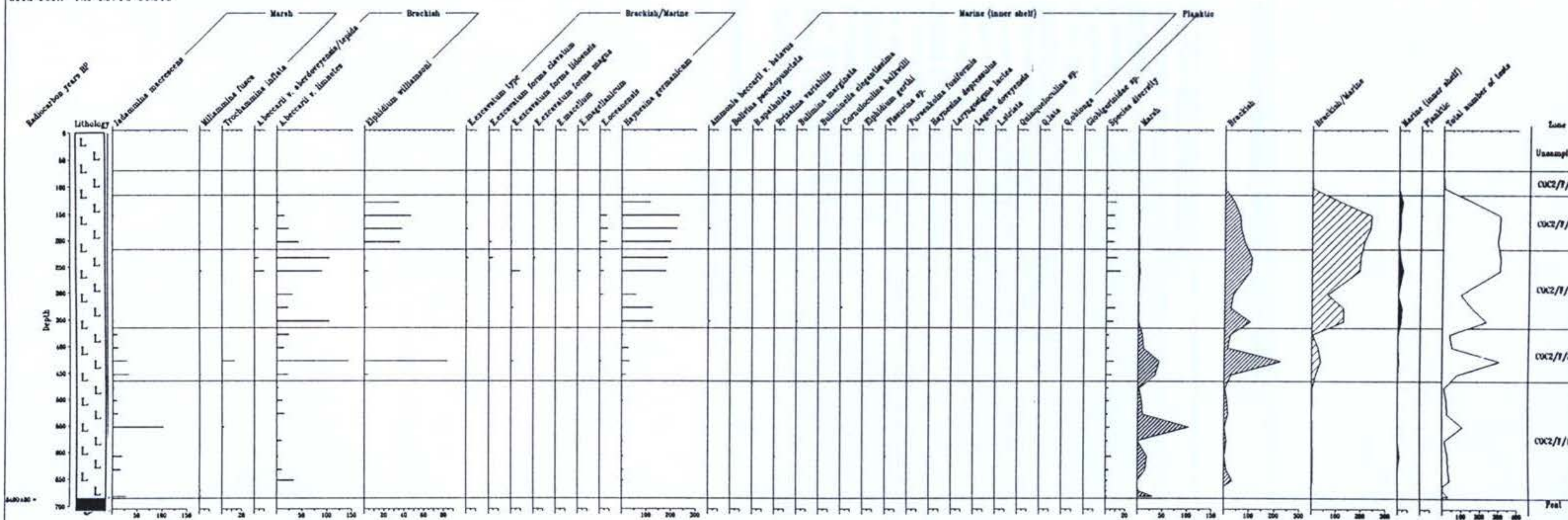
The characteristics of this phase are very similar to the previous one with both *J. macrescens* and *A. limnetes* still well represented. The main changes are the increased presence of *H. germanica* and the appearance of additional species including *E. williamsoni*. This phase appears to be at a transitional stage between a vegetated saltings environment and a high intertidal mudflat.

COC2/F/3 5.63 to 7.11m O.D. [Depth: 217-365cm]

Haynesina germanica is the dominant species of this phase with *A. limnetes* also well represented. The brackish and brackish/marine *Elphidium* sp. are frequently recorded and appear to be more common in the upper half of the phase. The presence of marine (inner shelf) species increases although no one species is in significant numbers. The agglutinating *J. macrescens* that characterised the previous two phase only records the occasional presence in this one. Species diversity rises to *circa* 10 per level. The foraminifera indicate an environment of deposition that approximates to a high intertidal mudflat.

Figure 7.22 Carse of Clary: Foraminifera

Borehole: COC/2
Height: 9.28m O.D.
Grid ref.: NX 42713 60248



COC/2 Foram. Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of foraminifera phase
COC/F/5	**8.58-8.13** 70-115	**Very low values of tests (barren)** Foraminifera abundance is very low and occasionally levels are barren. This is attributed to poor preservation rather than absence of species.
COC/F/4	**8.13-7.11** 115-217	***H. germanica - E. williamsoni - A. limnetes - E. oceanensis*** *H. germanica* dominates this phase. Numbers of *A. limnetes* fall off toward the top of the phase. *E. williamsoni* is consistantly present throughout. *E. oceanensis* is recorded in three of the four levels in this phase.
COC/F/3	**7.11-5.63** 217-365	***H. germanica - A. limnetes - Elphidium* spp.** This phase is dominated by *H. germanica* with *A. limnetes* also well represented. There is an increase in the presence of *Elphidium* spp. toward the top of the phase. The marsh species that dominated the two lowermost phases are now all but absent. Species diversity has increased.
COC/F/2	**5.63-4.63** 365-465	***J. macrescens - A. limnetes - H. germanica*** As for COC/F/1 but with the increased presence of *H. germanica* and the appearance of *E. williamsoni*.
COC/F/1	**4.63-2.43** 465-685	***J. macrescens - A. limnetes*** Low but consistant values of both *J. macrescens* and *A. limnetes*. *H. germanica* records a presence in most levels. The two agglutinating *T. inflata* and *M. fusca* are also recorded.

Table 7.11 Main characteristics of foraminifera phases in core COC/2, Carse of Clary.

COC2/F/4 7.11 to 8.13m O.D. [Depth: 115-217cm]

Haynesina germanica remains the dominant species. Values of *A. limnetes* fall off toward the top of the phase. *Elphidium williamsoni*, however, is consistently present in relatively high values throughout. *Elphidium oceanensis* is present in three of the four sampled levels. This association of species correlates well with that found on the low intertidal mudflats that are close to the open marine waters of Wigtown Bay (see Chapter 4).

COC2/F/5 8.13 to 8.58m O.D. [Depth: 70-115cm]

There is a sharp fall in foraminifera abundance in this phase with no tests recorded in one level. It is probable that the absence of foraminifera is related to poor preservation resulting from the affects of modern farming practices. No environment of deposition is inferred from the limited evidence.

7.8.2 COC/2: Ostracod analysis (Figure 7.23; Table 7.12)

Ostracod analysis on the sampled core taken from Carse of Clary has allowed the identification of three phases (Figure 7.23). The main characteristics and species associations of each phase are summarised in Table 7.12. Throughout the sequence low numbers of ostracods are present with only one level exceeding 200 valves. Twelve species have been identified. The buried peat deposits and the uppermost 70cm of the carse were not sampled for ostracods.

COC2/O/1 2.43 to 2.61m O.D. [Depth: 667-685cm]

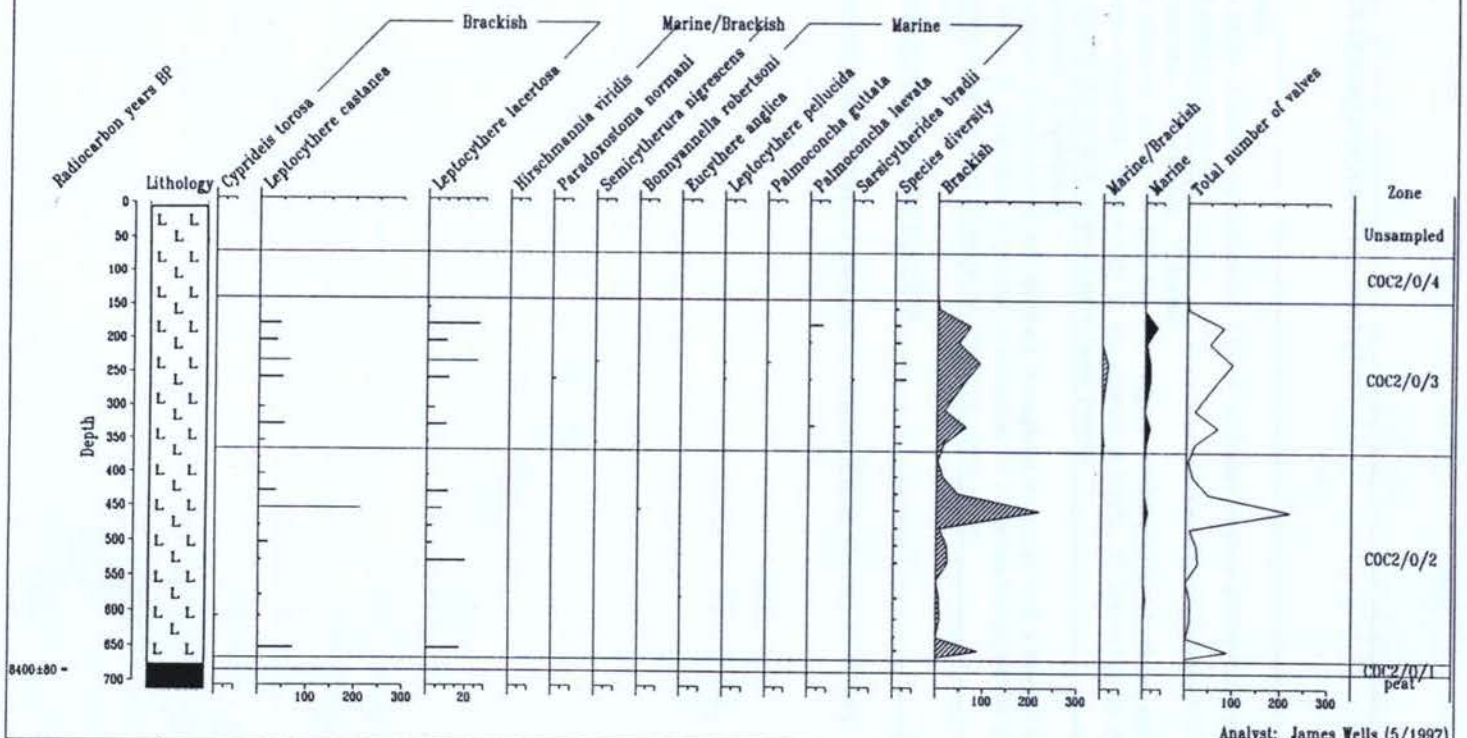
This phase immediately above the buried peats is barren of ostracod. It is possible that this absence represents the vegetated saltings terrace where ostracods are commonly absent.

COC2/O/2 2.61 to 5.63m O.D. [Depth: 365-667cm]

Leptocythere castanea is common in low numbers throughout the phase with a marked peak at 450cm. *Leptocythere lacertosa* is present in a number of the levels but is clearly more common in the top half of the phase. Few other species are recorded which is reflected in the low species diversity. In the lowermost half of the phase the low abundance values probably indicates a lower saltings terrace environment where the valves would be an allochthonous component. The upper half of this phase, where abundance increases, probably represents a transition to an unvegetated intertidal mudflat.

Figure 7.23 Carse of Clary: Ostracods

Borehole: COC/2
Height: 9.28m O.D.
Grid ref.: NX 42713 60248



COC/2 Ostracod Phase	Altitude (m O.D.) Depth (cm)	Main characteristics of ostracod phase
COC/O/4	**8.58-7.88** 70-140	**Barren** This phase is barren of ostracods. This is attributed to poor preservation rather than absence of species.
COC/O/3	**7.88-5.63** 140-365	***L. castanea - L. lacertosa - P. laevata*** This phase is similar to O/2 but with higher numbers of *L. castanea* and *L. lacertosa* recorded - particularly in the uppermost levels. *P. laevata* is the most common of the more diverse ostracod fauna present.
COC/O/2	**5.63-2.61** 365-667	***L. castanea - L. lacertosa*** *L. castanea* is common in low numbers throughout the phase with a marked peak at 450cm. *L. lacertosa* is present in a number of the levels but is clearly more common in the top half of the phase. Poor species diversity.
COC/O/1	**2.61-2.43** 667-685	**Barren** Ostracods are barren from this phase.

Table 7.12 Main characteristics of ostracod phases in core COC2, Carse of Clary.

COC2/O/3 5.63 to 7.88m O.D. [Depth: 140-365cm]

Leptocythere castanea and *L. lacertosa* both record higher values in this phase and there is a subtle trend of increasing values toward the uppermost levels. Numbers of Marine/Brackish and Marine species (diversity between 5 and 10) have also increased which, although probably allochthonous, suggest an increasing tidal influence. *Palmoconcha laevata* is the most well represented of these species. This assemblage is indicative of an intertidal mudflat.

COC2/O/4 7.88 to 8.58m O.D. [Depth: 70-140cm]

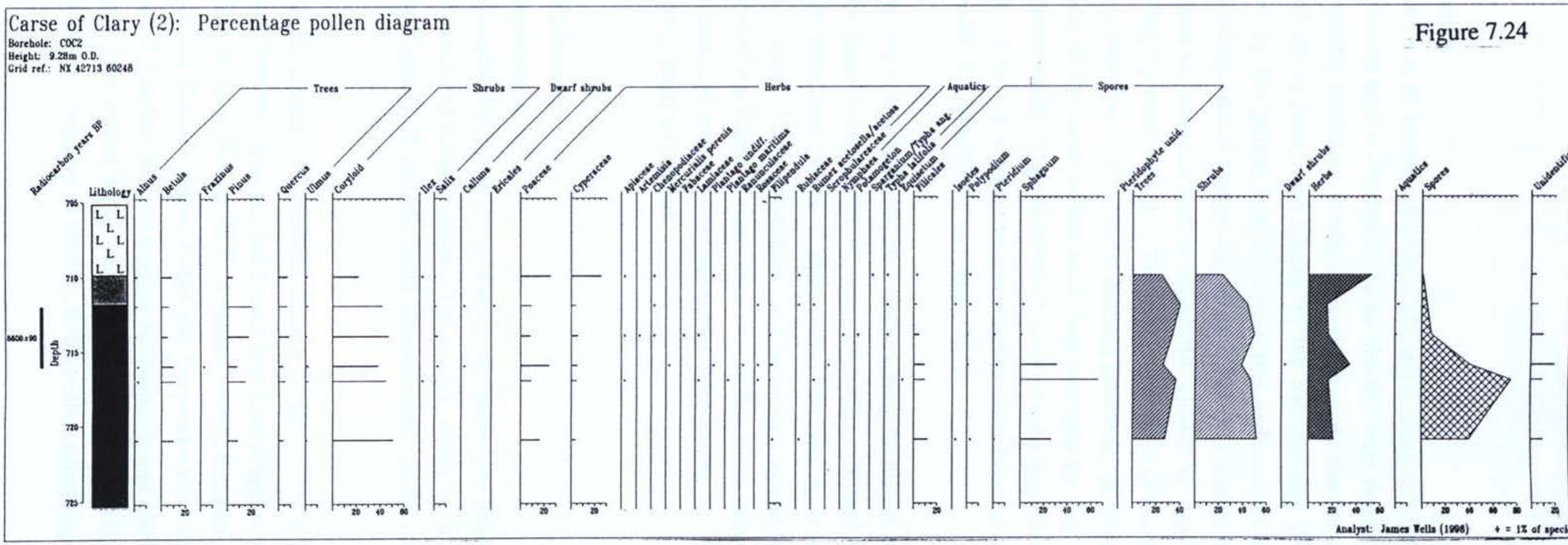
This phase is barren of ostracoda. The sharp fall in values from the previous phase is distinctive. The same conclusions arrived at for COC2/F/5 are suggested.

7.8.3 COC/2: Pollen analysis

Pollen analysis was undertaken across the boundary between buried peat and overlying carse at COC/2 to establish continuity of sedimentation. The results have not been zoned.

Altitude: 2.03-2.23m O.D. [Depth: 725-705cm] (Figure 7.24)

Coryloid values (*circa* 40%) are the dominant pollen in this core which indicate a decrease in numbers into the overlying carse (20%). Of the tree species present *Betula*, *Pinus* and *Quercus* are the most common with none recording less than 5% of TLP in any level. *Ulmus* and, to a lesser degree, *Alnus* are present in all levels but never more than 5% of TLP. Poaceae values fluctuate throughout the assemblage between *circa* 10% and 25%. Cyperaceae values are consistently low at 5% apart from a peak in the uppermost level at 23%. Of the other herbs that record a presence *Filipendula* is most common. Spore values are high (up to 75% of TLP) in the peats mainly comprised of *Sphagnum* and Filicales but decline sharply into the overlying carse. A mixed woodland of birch, pine, oak, elm and alder amongst hazel is indicated by the pollen. The presence in low but consistent values of *Alnus* pollen is noticeable and probably indicates an early stage of the alder rise. Herb and spore diversity and percentages are high probably indicating that the estuarine environment was well vegetated primarily by grasses and sedges. The pollen assemblages outlined here indicate that there was no erosional hiatus following inundation of the peats by rising relative sea-levels leading to the deposition of the carse sediments. One sample from the buried peat/carse boundary was subsequently sent for radiocarbon dating (8,600±90 ^{14}C years BP [Beta-96323]), full details of these are provided in Table 7.1.



Carse of Clary (2): Percentage pollen diagram

Figure 7.24

7.8.4 Summary of results

The top of the buried peat is at an altitude of 2.43m O.D. and is dated at 8,600±90 ^{14}C years BP. The early Flandrian peat is overlain by carse silts that were deposited in an environment that was probably a saltings terrace. This would imply that the top of the peat deposits were unlikely to have been eroded by the transgressing sea. This conclusion is supported by the pollen analysis across this sedimentary boundary which indicates a gradual vegetational change. By *circa* 4.75m O.D. a clear transition to low intertidal mudflats commences that is apparently closest to open marine conditions of Wigtown Bay by *circa* 7m O.D.. The uppermost metre of this sequence has been affected by the disturbance of modern farming practices. It is envisaged however that the surface of the carse would have been overlain by peat prior to reclamation. A date of *circa* 4,000 ^{14}C years BP for the end of carse deposition at this location is suggested based on the comparable carse/surface peat boundary dates at Carsegowan Moss (Beta-84189, Beta-83746 and Beta-83747).

The presence of *Alnus* pollen in low but consistent values across the buried peat/carse boundary which has been dated to *circa* 8,600 ^{14}C years BP is clear. Within this study no earlier record of such consistent values of alder pollen has been recorded. It is possible that a small population of *Alnus* colonised the Cree estuary region during the early Flandrian very close to the Carse of Clary location. If this is the case then the pattern of *Alnus* colonisation and spread across the British Isles during the Flandrian, as recorded by Birks (1989), must be revised.

7.9 Moss of Cree (Baltersan)

7.9.1 BAL/A3: Pollen analysis

Borehole BAL/A3 was sampled for pollen analysis across the carse/peat intercalations in order to establish continuity of sedimentation. The results, which have not been zoned, are presented in Figure 7.25 and the main characteristics of the pollen are described below.

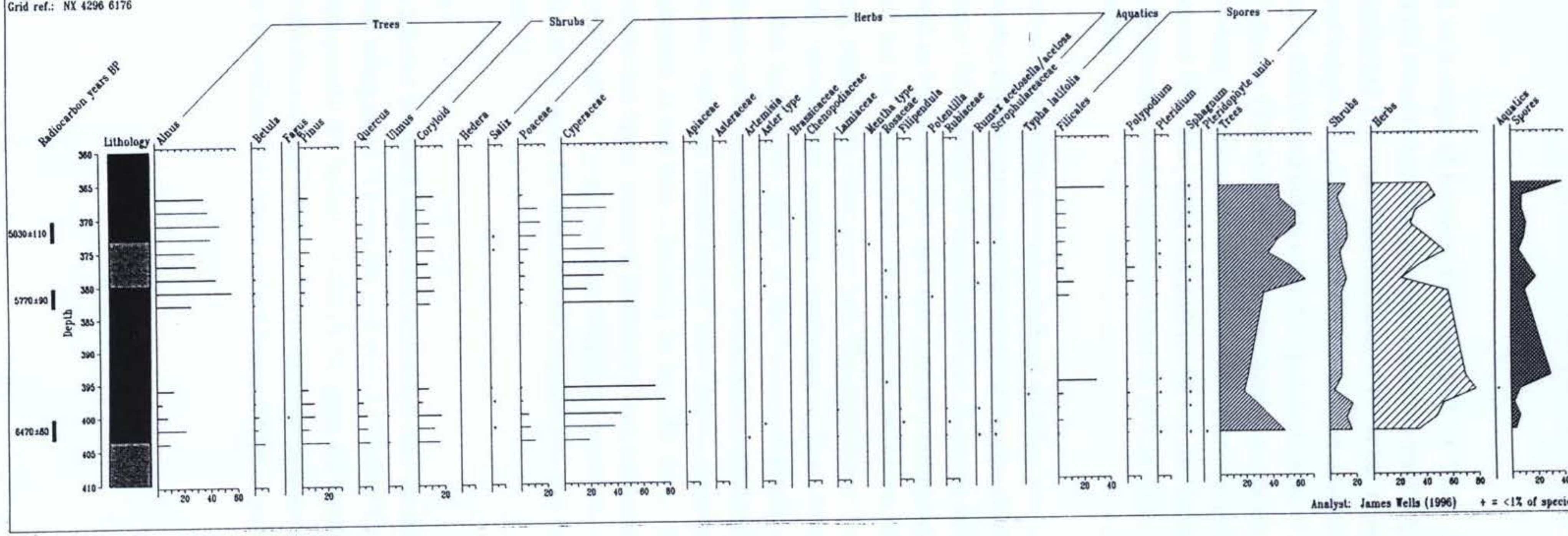
Altitude: 8.76-9.26m O.D. [Depth: 410-360cm] (Figure 7.25)

Across the lower junction between carse and the buried peat layer Cyperaceae pollen values increase from 20% to *circa* 70% of TLP. Poaceae values, however, fall into the peats as do *Quercus* and *Betula*. *Alnus*, *Pinus* and Coryloid values across this boundary retain a degree of stability with all ranging between 5% and 20% of TLP. Spore values are low apart from a peak in the peats of Filicales at 30% of TLP. In the upper peat/carse intercalations the degree of stability in the pollen assemblage is high.

Figure 7.25

Baltersan (Moss of Cree): Percentage pollen assemblage

Borehole: BAL/3
Height: 12.86m O.D.
Grid ref.: NX 4296 6176



Alnus values have increased to a range of between 25% and 55% of TLP. The stability is further reflected in the *Pinus* (*circa* 7%), *Quercus* (*circa* 5%) and Coryloid (*circa* 11%) curves. Both *Betula* and *Pinus* are recorded in most levels but never at more than 2% of TLP. Poaceae values are initially low at 5% before increasing across the carse/surface peat junction to 15% before tailing off in the uppermost level at 3%. Cyperaceae values fluctuate between 15% and 55% of TLP but these changes are not marked. Of the other herbs *Aster* is present in all levels in low numbers (<2%). Stability in the numbers of spores (Filicales, 10%; *Polypodium* 5%) is also recorded with only one marked peak in Filicales in the uppermost level at 35% of TLP. No depositional lacunae are indicated.

The results of the pollen analysis record that a mixed woodland of alder, pine, oak, birch, elm and hazel was probably close by during the deposition of the estuarine silts and terrestrial peat intercalations. Throughout the same time period, however, sedges, grasses and ferns are indicated as being abundant and were probably occupying the vegetated saltings terrace and on the bog surface. The diversity and nature of the other herb species, including particularly *Aster* type and Chenopodiaceae, would appear to reflect the close vicinity of estuarine conditions. The changing representation of *Alnus* is also noteworthy where in the lowermost levels alder appears well established but only as an equal component of the mixed woodland. In the uppermost levels, however, the high percentage of alder pollen suggests its dominance of the local vegetation at this time - probably as an alder carr. Three samples from the lower, middle and upper sediment boundaries were subsequently sent for radiocarbon dating (6,470±80 ^{14}C years BP [Beta-96322], 5,770±90 ^{14}C years BP [Beta-96321] and 5,030±110 ^{14}C years BP [Beta-96320] respectively), full details of these are provided in Table 7.1.

7.9.2 Summary of results

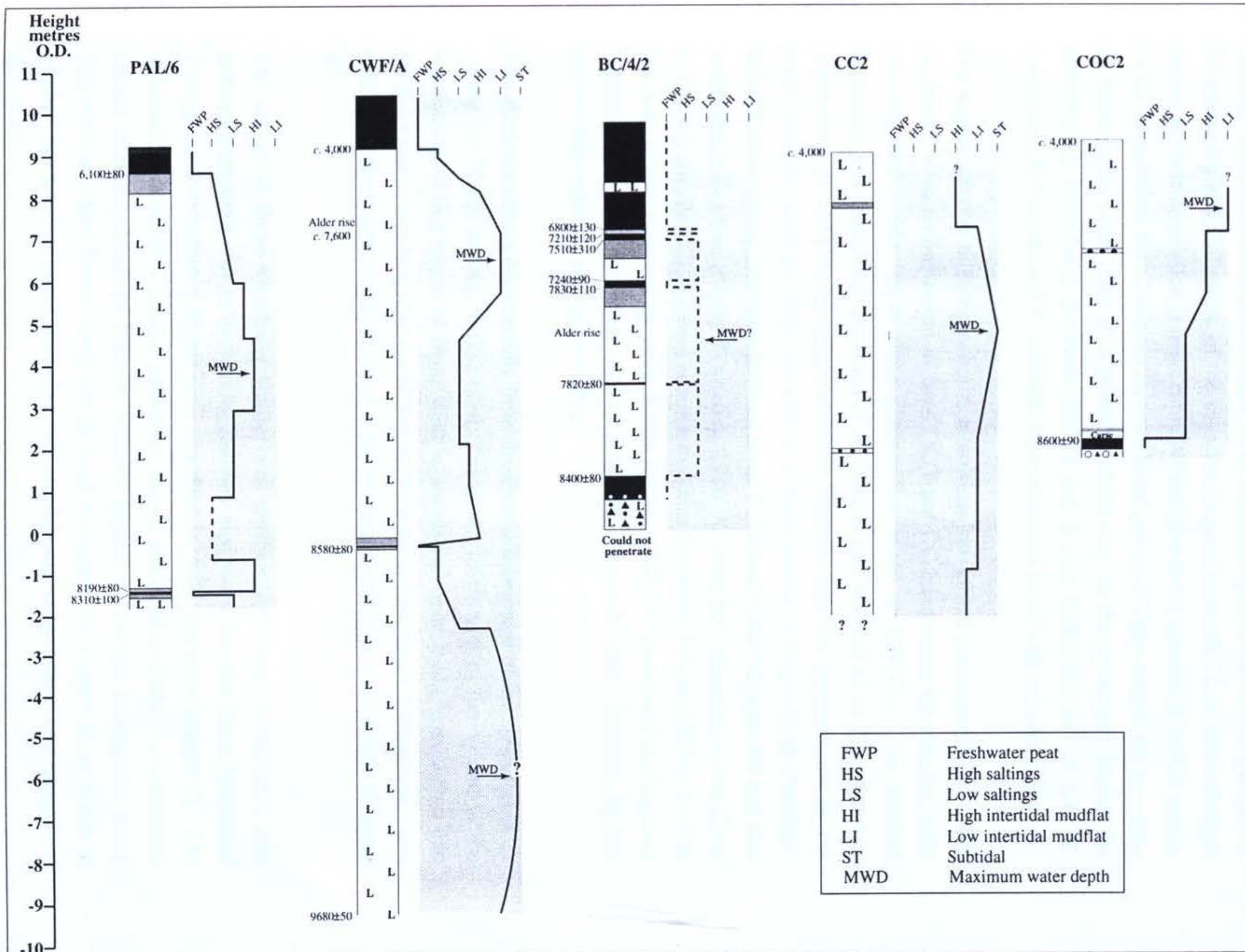
The results indicate that a relative sea-level regression occurred at this location at 6,470±80 ^{14}C years BP before rising again to cover the peat after 5,770±90 ^{14}C years BP. Relative sea-levels subsequently fell before 5,030±110 ^{14}C years BP when peat formation returned. Due to the limited distribution of this intercalation it is uncertain whether this is a local sea-level oscillation or whether it is a regional relative sea-level signature.

7.10 Discussion

7.10.1 Palaeoenvironmental correlation between cores

In Figure 7.26 the five boreholes PAL/6, CWF/A, BC/4/2, CC/2 and COC/2 are detailed showing in the broadest terms changing estuarine environment/water depth based on the microfaunal reconstructions. Between core correlations are made difficult by the paucity of radiocarbon dates - nonetheless similarities in the pattern of changing water depth are evident. The early Flandrian sediments in CWF/A cannot be compared with any of the other boreholes. The evidence from CC/2 does, however, show clearly that this site is a possible middle Flandrian analogue for the early Flandrian estuarine sequence. The mid-Flandrian sediments from the BC/4/2 site contain a poor microfauna. The limited evidence at this location indicates that it probably was not lowered to below a vegetated saltings environment - it is conceded that the alternations between minerogenic and organic deposits may not necessarily reflect regional relative sea-level changes. This suggestion is based on local geomorphological evidence and the absence of comparable intercalations elsewhere in the Cree estuary carselands.

The best correlation can be made between the two locations of PAL/6 and CWF/A where two phases of deepening and shallowing can be identified in the mid-Flandrian estuarine sequence. Each location records a rapid deepening immediately above the buried peat layer which, through stratigraphic correlation and radiocarbon dating, was formed synchronously at the two sites. At both locations this peak is followed by a shift to a saltmarsh environment. At PAL/6 the return to intertidal mudflat deposition appears to occur much earlier in the sequence (accounting for consolidation of the silts and clays) than at CWF/A where the initial intertidal mudflat phase was more prolonged. Indeed the start of the second phase of intertidal mudflat deposition at CWF/A appears to correspond with the synchronous return to a saltmarsh environment at PAL/6. This interchange of depositional environments between the two locations probably reflects the changing positions of the Cree river channel and its tributaries. Whether these changes are a response to rising relative sea levels is uncertain. Whatever the case a correlation between the uppermost levels at the two locations is made more complex where it is shown from the radiocarbon dates that the sediments recorded at CWF/A continued to form under estuarine conditions for at least 2,000 more years before peat formation was initiated.


Height metres O.D.
PAL/6
CWF/A
BC/4/2
CC2
COC2
FWP HS LS HI LI ST
6,100±80
8190±80
8310±100
c. 4,000
Alder rise c. 7,600
8580±80
9680±50
6800±130
7210±120
7510±310
7240±90
7830±110
Alder rise
7820±80
8400±80
Could not penetrate
MWD
MWD?
8600±90
FWP Freshwater peat
HS High saltings
LS Low saltings
HI High intertidal mudflat
LI Low intertidal mudflat
ST Subtidal
MWD Maximum water depth

The similarities between CC/2 and COC/2 on the western side of the valley are striking. The microfaunal assemblages do not necessarily correlate but the patterns in the deepening and shallowing of the sequences appear to match. It is acknowledged that an accurate correlation is made more difficult due to the absence of buried peat at CC/2. Nonetheless both locations record a broad pattern of deepening in the sequence up through the carse prior to a probable shallowing in the uppermost levels; the similarity in microfauna between CC/F/4 and 5 and COC2/F/3 and 4 (i.e. *H. germanica*, *A. limnetes* and *E. williamsoni*) is clear and is unlikely to be coincidental.

The suggestion that this deepening is more than just a local phenomenon is further reinforced when a comparison of the COC/2 and CC/2 sequences are matched with that recorded in the upper three foraminifera zones at CWF/A. The marked deepening and shallowing sequence is as clear at this location as in the other two sequences. At CWF/A the pollen evidence indicates that this apparent rise in sea level coincides with the alder rise which is dated nearby at Blairs Croft (borehole BC/4/2) as occurring sometime between *circa* 7,800 and 7,200 ^{14}C years BP and also at Brighouse Bay (see chapter 5) to *circa* 7,700 ^{14}C years BP. However, at the Carse of Clary (borehole COC/2) there is some evidence that *Alnus* had established itself in this area in low numbers by *circa* 8,600 ^{14}C years BP. Nonetheless, this regional vegetational event correlates closely with the brackish marl deposits in the sedimentary sequence at Brighouse Bay.

This evidence differs considerably from the current knowledge of the spread of alder during the Flandrian (e.g. Birks, 1989; Tallantire, 1992) both in timing and in the relationship of this spread to rising relative sea-levels. Here it has been shown that the alder rise occurs long after the initiation of the Main Postglacial Transgression and only really flourishes during a period of relative sea-level fall at *circa* 4,000 ^{14}C years BP.

The timing of these apparently similar and synchronous coastal evolution events perhaps goes some way to explaining Jardines' suggestion that the Main Postglacial Transgression culminated at this time (see Jardine, 1975 and also Chapter 2). The absence, however, of a similar pattern of coastal evolution at PAL/6 is noticeable; indeed as stated above the Palnure evidence appears to indicate an opposite trend. The evidence from Blairs Croft can be used to support the suggestion of a rise in relative sea level at about this time but overlapping dates makes any correlation tentative.

7.10.2 Implications for relative sea-level change and coastal evolution

The microfauna of the silts that underlie the carse and a buried peat layer at location CWF/A indicate that they were deposited under brackish/estuarine conditions. Cold (Arctic) water ostracoda and foraminifera are recorded infrequently and in low numbers. These could indicate water temperatures lower than present or they may represent a legacy from Lateglacial microfaunal populations in this region. Equally, and most probably, they could be an allochthonous component of the assemblage having been reworked from cold-water sediments in the area. The dominance of the two species *L. castanea* (ostracod) and *H. germanica* (foraminifera) that are common to the British Isles at present (see Athersuch *et al.*, 1989 and Murray, 1979 respectively) indicate that the water temperatures indicated by the microfauna were probably similar to present. Further a radiocarbon date of 9,680±50 ^{14}C years BP (Beta-92209) on shells (*Cerastoderma edule*) that were probably *in situ* (based on the ecological relationship of this species with the foraminifera and ostracod assemblage from this sample) from the base of the core taken from CWF/A indicates that the silts above -9.37m O.D. were formed during the early Flandrian. Due to the contamination in the shells by "old carbon" from sea water this date should be corrected by *circa* 425 years (a figure calculated from modern shell dates around the British coasts - see Chapter 3 and also Sutherland, 1983) to *circa* 9,250 ^{14}C BP. Evidence for estuarine (marine) and/or terrestrial sediments deposited during the Younger Dryas possibly exist deeper in the sequence of sediments. It is probable, however, that the lower silts continue for some metres with the microfauna indicating an increasing water depth down sequence.

For the most part of the lower estuarine sediments the environment of deposition is almost certainly one of a low intertidal mudflat or possibly even a subtidal mudflat. Only in the uppermost levels of these sediments is there the indication of a vegetated saltings terrace positioned above Mean High Water of Spring Tides. In the overlying carse sediments at CWF/A a similar environment of low intertidal mudflats is achieved infrequently. Of the other locations also investigated only CC/2 records a carse microfauna that reflects a similar depositional environment to the early Flandrian estuarine deposits over such a long sequence of sediments. This probably indicates that the CWF/A location during the early Flandrian was more influenced by the open waters of Wigtown Bay. If this is the case then the size and extent of the intertidal zone of the early Flandrian estuary was clearly smaller than at any other time during the Flandrian.

Carse deposition at CWF/A and PAL/6 was apparently initiated by at least *circa* 8,300 ^{14}C years BP. Microfauna recorded in the carse sediments of these two boreholes that overlie buried peat are not indicative of a vegetatated saltings environment but have an intertidal mudflat association indicating the strong possibility of an erosive contact at each location. However, at locations BC/4/2 and COC/2 the buried peat deposits - which records the oldest of the dates on the transgressive contact - is overlain by sediments deposited in an estuarine intertidal saltings environment. This situation is an apparent paradox where the 'erosive' contacts of the buried peats in PAL/6 (*circa* 8,200 ^{14}C years BP) and CWF/A (*circa* 8,600 ^{14}C years BP) would be expected to record a relatively older date to those which are not eroded at COC/2 and BC/4/2 (*circa* 8,600 and 8,400 ^{14}C years BP respectively). Radiocarbon errors provide the only plausible explanation for these apparent inconsistencies. It is also very possible that the degree of compaction of the buried peats was so great that even with a 2-3cm sample the "contamination" from older peats increased the apparent age significantly.

The radiocarbon dates for the regressive contact of peat overlying the carse in the Cree estuary appears to vary greatly between *circa* 6,800 ^{14}C years BP at Blairs Croft, *circa* 6,100 ^{14}C years BP at Palnure and *circa* 4,000 ^{14}C years BP at Carsewalloch Flow, Carsegowan Moss and the Moss of Cree. The microfaunal evidence provides no insight into the reasons for these timing differentials. The differences in age can in part be explained by the evidence from Baltersan (northern end of the Moss of Cree) where the regression from the main carse surface is at *circa* 6,500 ^{14}C years BP yet a later transgression and regression appears to have taken place between *circa* 5,800 and 5,000 ^{14}C years BP. This still leaves a *circa* 1,000 ^{14}C year differential in the timing of regression from the southern most area of the carselands. It is possible that a relative sea-level "standstill" occurred during this time where land uplift, sea-levels and sedimentation rates maintained an equilibrium. Alternatively a more subtle and indistinguishable sea-level fluctuation during this 1,000 year period may have taken place.

7.10.3 Accumulation rates

To calculate the accumulation rate of a sedimentary unit the calibrated timescale has to be employed to aquire an annual figure. In this exercise "accumulation rates" are taken as the amount of sediment deposited in millimetres per year (mm/yr) of a sediment column which is constrained by two calibrated dates. Here only the maximal calibrated age of the older date and the minimal calibrated age of the younger date are used to determine the absolute minimum rate of sedimentation.

The opportunity to investigate the microfauna and date the thick sequence of lower estuarine sediments was only afforded at the location CWF/A. Here *circa* 9m of silts and clays have been constrained by two radiocarbon dates that indicate deposition to have occurred over a 750 (radiocarbon) year timespan between *circa* 9,250 and 8,600 ^{14}C years BP. Unfortunately the Pretoria calibration curve used to calibrate the radiocarbon ages of each date did not extend back as far as the date on the marine shell (Beta-96325). However, because this particular date has been corrected by *circa* 425 years (see above) the calibrated age can be calculated on the approximate date of 9,255 ^{14}C years BP. Using the calibration curve of Kromer *et al.* (1995) a calibrated age of *circa* 10,100 cal. yrs. BP has been established. The minimal age of the younger (uppermost) date is 9,430 cal. yrs. BP and the precise distance between the two dates is 8.8m. This approximates to a minimum rate of sedimentation of *circa* 13.1mm/yr of sedimentation in the early Flandrian estuarine sediments.

The *circa* 9m of mid-Flandrian carse sediments at the same location are similarly constrained between *circa* 8,600 and 4,000 ^{14}C years BP (extrapolated from CWF/6). The maximum calibrated age is 9,820 cal. yrs. BP (Beta-96325) and the minimum (Beta-83749) is 4,250 cal. yrs. BP with the precise thickness of the carse at CWF/A being 9.49m. This approximates to a minimum rate of sedimentation for the carse of 1.7mm/yr.. The apparent differential between the sedimentation rate of the early Flandrian estuarine sediments and that of the mid-Flandrian carse at CWF/A is 11.4mm/yr..

Using the same procedure for the carse sediments at Palnure (PAL/6), where carse deposition ended markedly earlier than at Carsewalloch Flow. Here a maximal and minimal date of 9,380 and 6780 cal. yrs. BP constrain precisely 9.73m of carse sediments. This approximates to a 3.7mm/yr. rate of sedimentation which differs markedly for that recorded at the CWF/A location. The differences in carse depth between the two locations is minimal. However, the Palnure location would almost certainly have been outside the furthest extent of the higher silt and clay layer recorded at Baltersan - a feature which may represent a mid/late Flandrian relative sea-level transgression. This interpretation would account for the differences in chronology of regression between Pal/6 and CWF/A. If this is accepted then it would indicate that the sedimentation rates during the mid-Flandrian are probably more comparable with the PAL/6 value. On this basis the rate of sedimentation in the Cree estuary during the early Flandrian was still three times that of the sediments deposited during the mid-Flandrian.

The sedimentation rates suggested here are only presented as an indicator of the broad differences between the carse and the earlier Flandrian estuarine sediments. The changing estuarine palaeoenvironments indicated by the microfauna, from high saltmarsh to sub-tidal mudflat, clearly show that to apply a one off sedimentation rate to such a sequence would be misleading. Further the differences in the apparent timing of the sea-level regressions/transgressions between locations and also between the new dates presented here for PAL/6 and those from the same boundary at Palnure provided by Jardine (1975) exemplify the complexity of the pattern of relative sea-level regression in this region during the mid-Flandrian. Nonetheless these simple comparisons appear to record a relatively rapid early Flandrian sedimentation rate which possibly reflects the vast quantities of sediments released at the end of the Younger Dryas.

7.11 Summary

Foraminifera and ostracod analyses of the deep sequence of deposits from the Cree estuary has revealed a complex series of changing estuarine palaeoenvironments, tendencies of relative sea-level and some insights into the evolution of the Cree estuary throughout the Flandrian. The silts and clays that lie buried beneath both the carselands and a buried peat layer have been confirmed as being of marine (estuarine) provenance. Unfortunately only in borehole CWF/A was a detailed investigation of these sediments possible, but this nonetheless revealed that during the early Flandrian between *circa* 9,250 ^{14}C years BP and 8,300 ^{14}C years BP the proto-Cree estuary was close to its present position. The size of the estuary at this time was probably much smaller than the intertidal area covered by the present estuary with the mouth of the river located close to the present position of Carsewalloch Flow.

In the early Flandrian estuary there is no evidence from the microfauna of cycles of negative and positive tendencies in sea-level. The only change recorded is one of a falling relative sea-level indicated by a gradual transition from (probably) a subtidal environment of deposition to intertidal and ending in high marsh prior to the formation of the buried peats. The rapidity of sedimentation during the early Flandrian in comparison to the carse is clear and probably was as a result of high sediment availability from both onshore and offshore following the end of the Younger Dryas. The extent of the buried peats is not completely established due to subsequent erosion by the rising relative sea-levels that deposited the carselands. Nonetheless, it would appear from their distribution that the peats would have covered a similar area to those that exist on the surface of the carselands today and would undoubtedly have continued up to the valley edge. This would by inference imply an early Flandrian Cree river/estuary channel in a position that approximates to its current one. Thus at *circa* 8,300 ^{14}C years BP the Cree estuary would have not looked dissimilar to the present albeit at a position in the valley *circa* 10m lower.

The pattern, extent and rate of mid-Flandrian relative sea-level changes has been shown to have been much more complex than was previously thought (i.e. Jardine, 1975). For instance, there is some evidence for a distinctive increase in the rate of relative sea-level rise during the Main Postglacial Transgression after 7,700 ^{14}C years BP from the microfossils in the carse sediments. In the following chapter the evidence presented here from the Cree estuary is used, in combination with the results from Brighouse Bay and West Preston, to construct an age-altitude graph of relative sea-level changes in this region.

Chapter 8 Relative sea-level changes in the Cree estuary region and the northern shoreline of the Solway Firth

8.1 Introduction

On the basis of the stratigraphical analyses from the Cree estuary (Chapter 7), Brighouse Bay (Chapter 6) and West Preston (Appendix A) the use of all radiocarbon dates as relative sea-level index points has been evaluated. The first section of this chapter utilises those dates that were considered suitable as index points to construct a relative sea-level age-altitude graph ("curve") for the Cree estuary region. In addition, to correct errors associated with the radiocarbon dating process, altitude error margins for each contact have also been estimated. Seven graphs are presented which use the same data but apply different correction factors (i.e. age and altitude) at each stage.

The second section of this chapter is a description and critical synthesis of relative sea-level changes and coastal evolution in the Cree estuary region based on all the morphological and stratigraphical evidence from this and previous studies. The final section is a detailed comparison and correlation exercise of the results from this study with Jardine's (1975; 1980) data for relative sea-level changes in the eastern Solway Firth (refer to Figure 2.6 for locations). It is hoped that by applying the model of relative sea-level changes developed in this thesis for the Cree estuary region to the less detailed evidence from the eastern Solway Firth, some of the anomalous differences between the Flandrian relative sea-level history for this region (Haggart, 1982; 1989) can be explained.

8.2 Altitude error calculations for each relative sea-level index point

Detailed below in Table 8.1 are the altitude error calculations for each of the radiocarbon dated relative sea-level index points. In this study the measurement error can be divided into two separate sets of values for each index point. There is the constant value that is applied to all index points and takes into account levelling error, benchmark accuracy and coastal landform surface error (see section 3.4.3). The variable error value is that which takes into account sediment compaction at each site (see section 3.4.5) and in this study the maximum compaction value of 68% on transgressive contacts, as calculated by Cullingford *et al.* (1980) in a comparable study, has been employed. Transgressive peat/carse contacts are affected by post-depositional compaction to a much greater degree than a regressive one where peat

Error	Magnitude
Datum errors - based on Ordnance Survey figures for bench mark accuracy (after Sutherland, 1981 in Gray, 1983)	±0.01m
Instrument errors - based on closing errors of levelled traverses and subsequent altitude correction (after Sutherland, 1981 in Gray, 1983)	±0.011m
Landform errors - based on variability of measurements on the same feature (after Sutherland, 1981 in Gray, 1983)	±0.45m
Sediment compaction error (positive correction in altitude only) - based on post-depositional estimates of peat compaction (after Cullingford *et al.*, 1982)	+ 68% of peat layer depth (C)
Total altitude error applied to each index point	**±0.47 + (C)**

Table 8.1 Altitude error magnitudes for each radiocarbon dated relative sea-level index point

Site/borehole	Lab. code	^{14}C date (years BP)	Age cal. Years BP (2 sigma) (* denotes max/min values)	Altitude (metres O.D.)	Altitude error	National Grid Ref. (NX)	Material	Environment	Sea-level Tendency	^{14}C Procedure
Hollanbank	GU-374	2027±108	1715 - 2312*	5.24	±0.47	482 555	Shell	Raised shell ridge/reg.?	Negative	Standard
Crook of Baldoon	I-5068	2290±95	2051 - 2706*	5.15	±0.47	440 530	Shell	Inter-/sub-tidal seds.?	Negative	Standard
Moss of Cree	I-5513	4000±100	4150 - 4823*	8.35	±0.47	445 614	Wood	Regressive contact	Negative	Standard
Muirfad	SRR-26	4746±50	5320 - 5594	7.92	±0.47	453 620	Wood	Regressive contact	Negative	Standard
Newton Stewart	Q-639	6159±120	6741 - 7270	4.25	±0.47	416 640	Wood	Inter-/sub-tidal seds.?	Negative	Standard
Palnure borehole	Birm-189	6240±240	6543 - 7541	6.38	±0.47	450 636	Wood	Regressive contact	Negative	Standard
Palnure borehole	Birm-415	6540±120	7206 - 7571	6.38	±0.47	450 636	Peat	Regressive contact	Negative	Standard
Carseminnoch	I-5514	6325±120	6905 - 7396	4.30	±0.47	443 626	Wood	Inter-/sub-tidal seds.?	None	Standard
Little Park	Birm-219	7450±200	7829 - 8564*	6.34	±0.47	450 657	Wood	Trans. and regressive?	Pos./Neg.	Standard
Bargaly borehole	Birm-188	7960±350	7997 - 9539	6.30	±0.47	596 589	Wood	Transgressive contact	Positive	Standard

Table 8.2 Relative sea-level index points determined from Jardine (1975)

overlies minerogenic sediments. For this reason in this study compaction of sediments is only calculated for transgressive contacts and it should therefore be clarified that this error value is always positive. Variation in palaeo-tide levels has been acknowledged elsewhere (section 3.4.4) but no meaningful correction value can be calculated for these changes over time and so is not included in the altitude errors here.

8.3 Radiocarbon dated relative sea-level index points

Of the radiocarbon dates acquired in this research 24 have been evaluated as being suitable as relative sea-level index points. These include 22 from the Cree estuary (excluding Beta-92209), 1 from Brighouse Bay (Beta-100913) and 1 from West Preston (Beta-84193). All details of radiocarbon dates have been presented elsewhere (Table 5.1, 7.1 and A.1). This information includes site code and borehole number, laboratory code, conventional radiocarbon age, age in calibrated years BP (2 sigma), altitude (metres OD), material, environment of deposition, relative sea-level tendency, radiocarbon procedure, national grid reference and the magnitude of altitude error.

8.4 A relative sea-level age-altitude graph for the Cree estuary region

8.4.1 Introduction

Using the radiocarbon dated index points a relative sea-level age-altitude graph for the Cree estuary can be constructed. Due to the non-standardised production of relative sea-level curves in comparable studies a series of seven sea-level curves, using the same data from this study, has been produced below that will allow comparison with nearly all published curve forms. A description and discussion of the relative sea-level changes in the Cree estuary follows.

8.4.2 M^1 relative sea-level age-altitude graph: Curve A

In curve A (Figure 8.1) all index points have been plotted at their recorded altitude. In similar studies these points are taken as the former position of MHWST (Tooley, 1978). However, in this study each index point is correlated with the former saltings level which does not equate to the MHWST point but to a level between the MHWST and HAT (see sections 4.2 and 4.3). For this reason the index points are taken to represent an altitude which approximates to the mid-point of these two tide levels (M^1) as suggested elsewhere (Shennan, 1986b). The conventional radiocarbon age is plotted with a two standard deviation error margin. The indicative relative sea-level tendency is also shown for each point using direction arrows. A single line 'best fit' curve (evaluated visually) has been included to give an indication of relative sea-level change.

8.4.3 M[1] relative sea-level age-altitude graph: Curve B

In curve B (Figure 8.2) each index point has been plotted as for curve A. However, the error magnitudes of altitude have been incorporated resulting in error boxes for each. Also a sea-level band has replaced the single line curve.

8.4.4 M[1] relative sea-level age-altitude graph: Curve C

For curve C (Figure 8.3) the radiocarbon ages have been changed to calibrated years BP and include a two standard deviation.

8.4.5 Mean Tide Level relative sea-level age-altitude graph: Curve D

In curve D (Figure 8.4) each index point has been plotted as for curve A but to allow for tidal variability and in accordance with previous investigations (e.g. Jardine, 1975; Tooley, 1978; Haggart, 1989; Long, 1992) the altitude of each index point has been reduced to a former Mean Tide Level (MTL) by subtracting the value of M[1] - MTL (measured at the nearest tide gauge station to each sample site) from their observed altitudes (see section 4.2 for details). The conventional radiocarbon age with one standard deviation, relative sea-level tendency and a visually evaluated single line 'best fit' curve are all included.

8.4.6 Mean Tide Level relative sea-level age-altitude graph: Curve E

In curve E (Figure 8.5), and as for curve B, the error magnitudes of altitude are included to the MTL-corrected index points. The error boxes formed are incorporated within a relative sea-level band.

8.4.7 Mean Tide Level relative sea-level age-altitude graph: Curve F

In curve F (Figure 8.6), and as for curve C, the radiocarbon ages have been changed to calibrated years BP and include a two standard deviation.

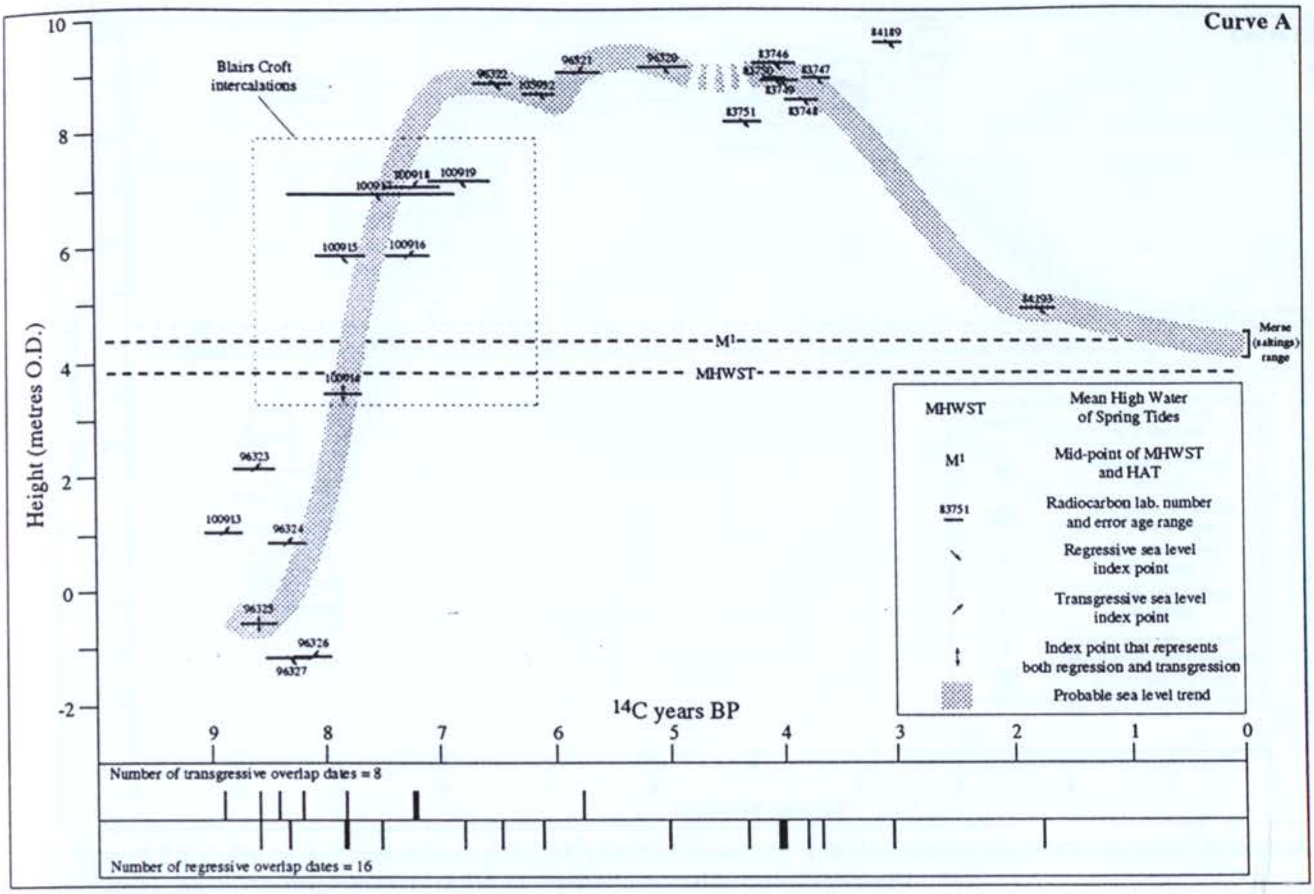


Figure 8.1 Relative sea-level age-altitude graph (M[1]) for the Cree estuary including index points from Brighouse Bay and West Preston (radiocarbon dates uncalibrated and to two standard deviations).

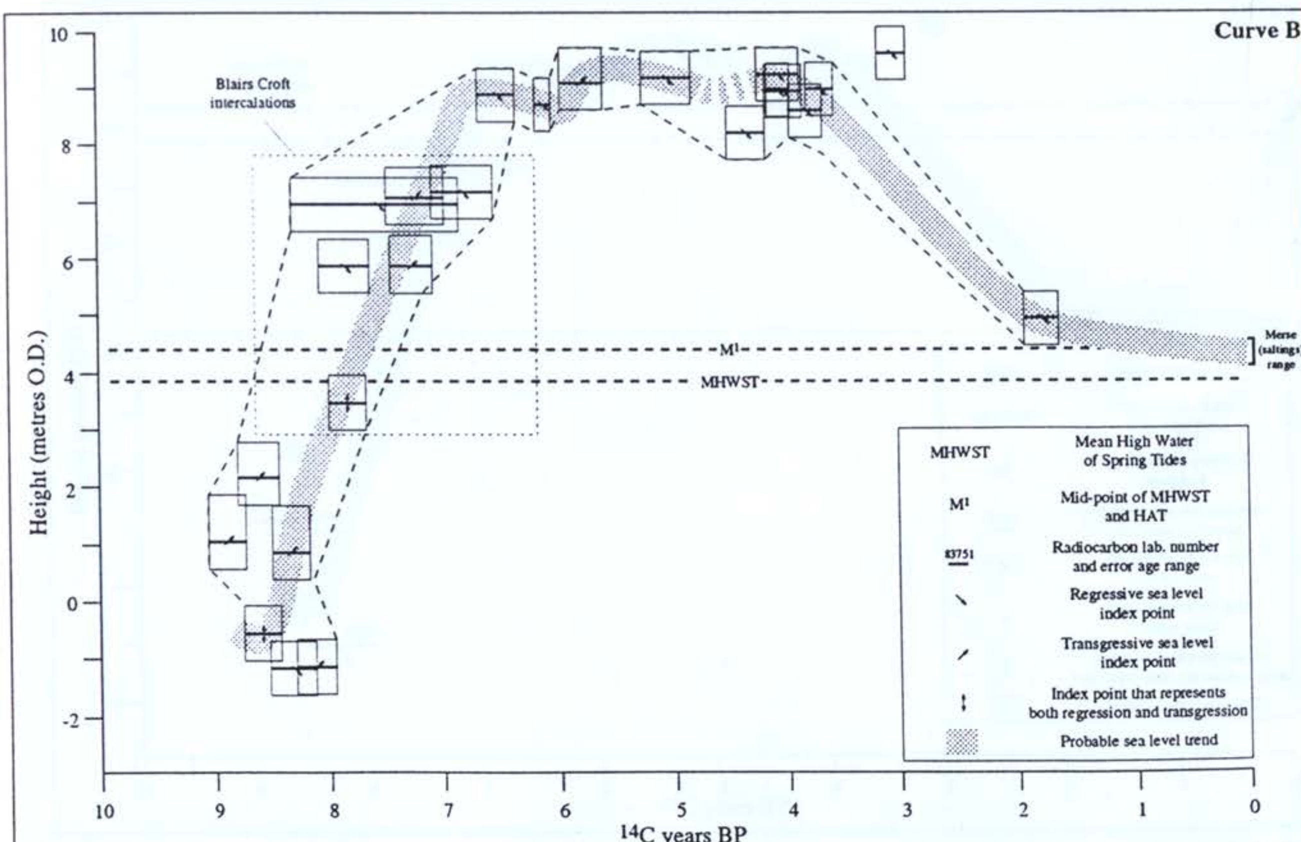


Figure 8.2 Relative sea-level age-altitude graph (M[1]) for the Cree estuary with altitude error magnitudes. Including index points from Brighouse Bay and West Preston (radiocarbon dates uncalibrated).

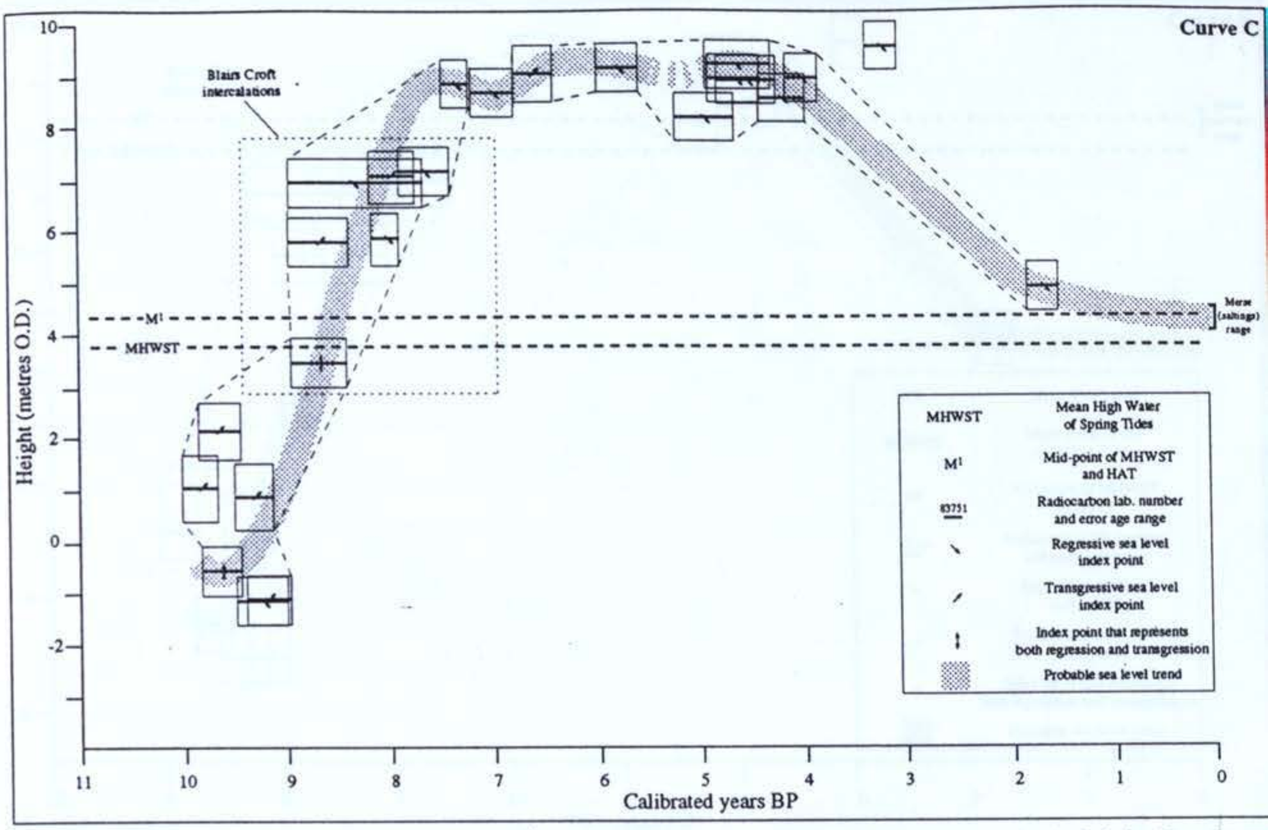


Figure 8.3 Relative sea-level age-altitude graph (M^1) for the Cree estuary with altitude error magnitudes included. Also shown are index points from Brighouse Bay and West Preston (radiocarbon dates calibrated).

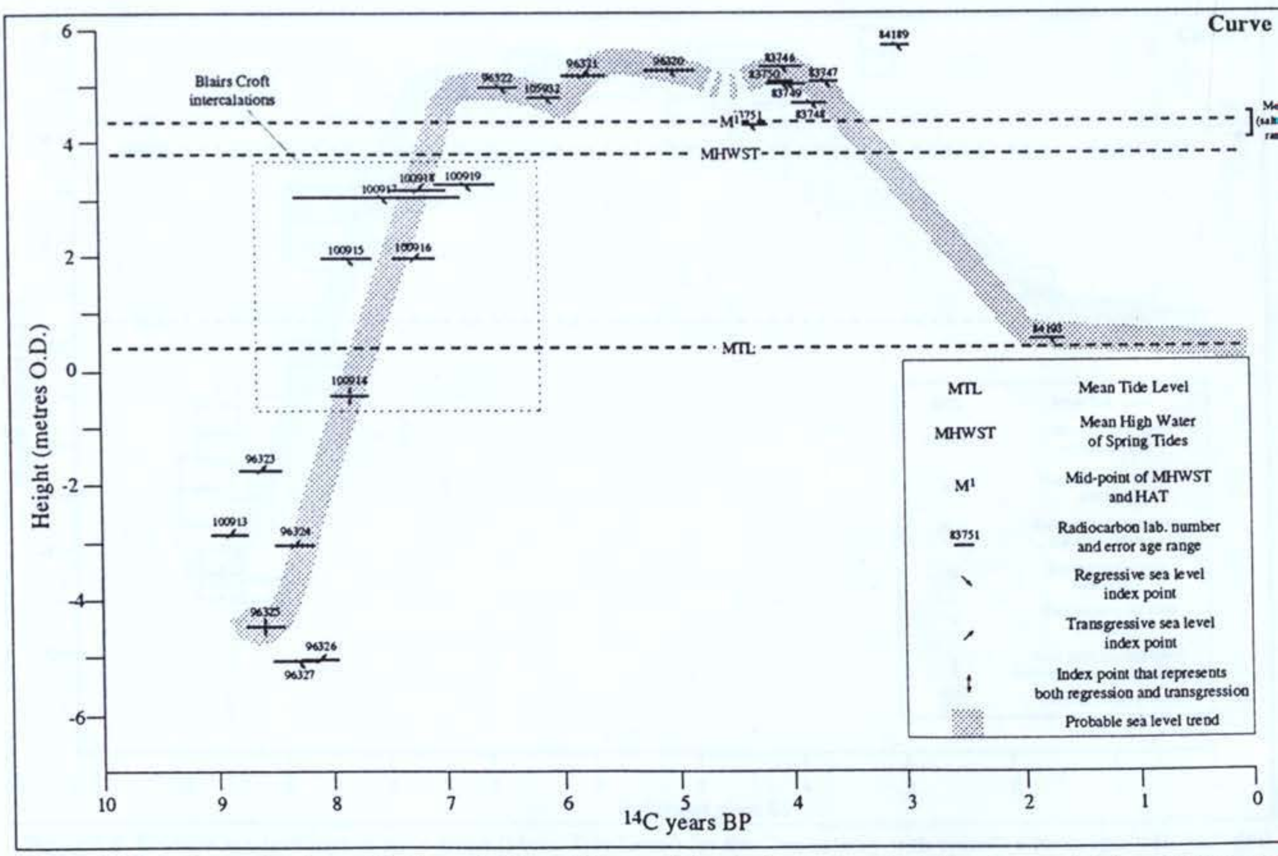


Figure 8.4 Relative sea-level age-altitude graph (Mean Tide Level) for the Cree estuary including index points from Brighouse B and West Preston (radiocarbon dates uncalibrated and to two standard deviations).

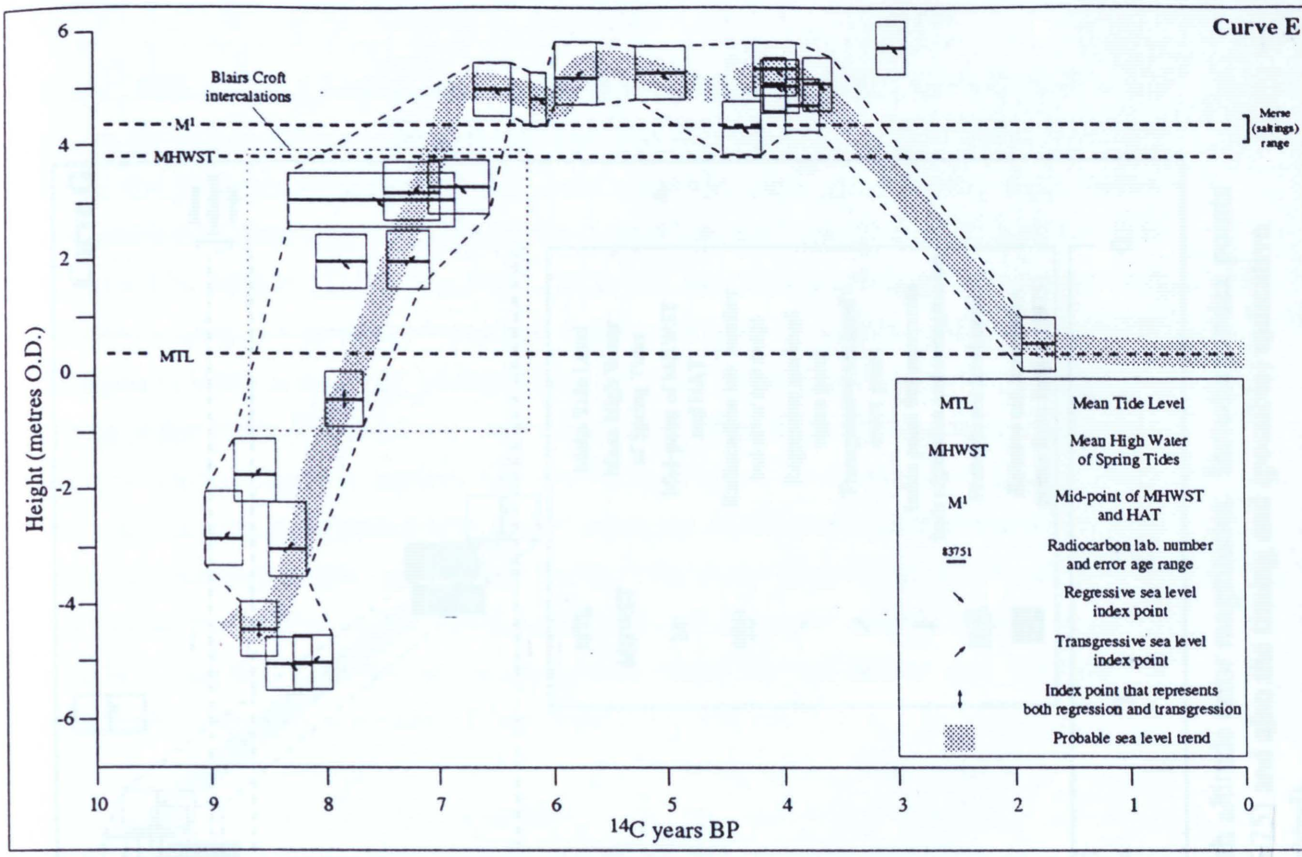


Figure 8.5 Relative sea-level age-altitude graph (Mean Tide Level) for the Cree estuary with altitude error magnitudes. Including index points from Brighouse Bay and West Preston (radiocarbon dates uncalibrated).

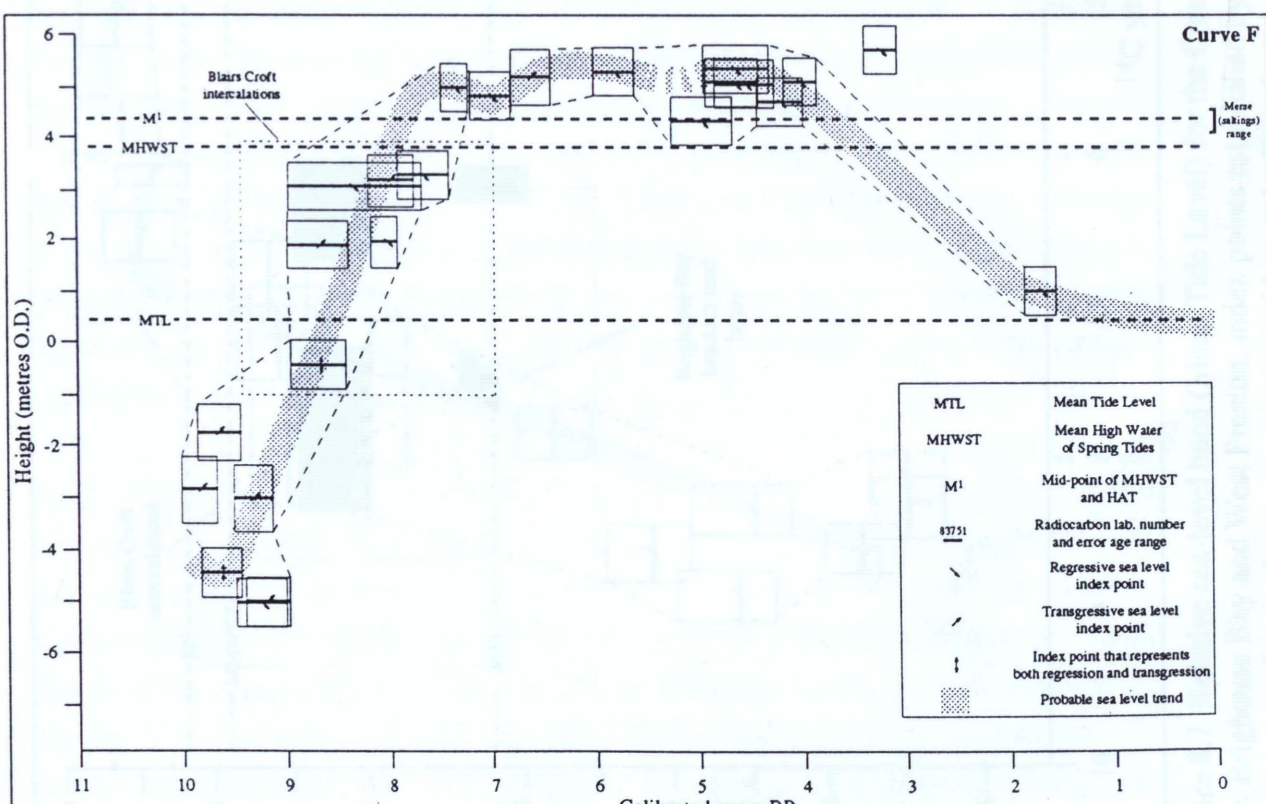


Figure 8.6 Relative sea-level age-altitude graph (Mean Tide Level) for the Cree estuary with altitude error magnitudes included. Also shown are index points from Brighouse Bay and West Preston (radiocarbon dates calibrated).

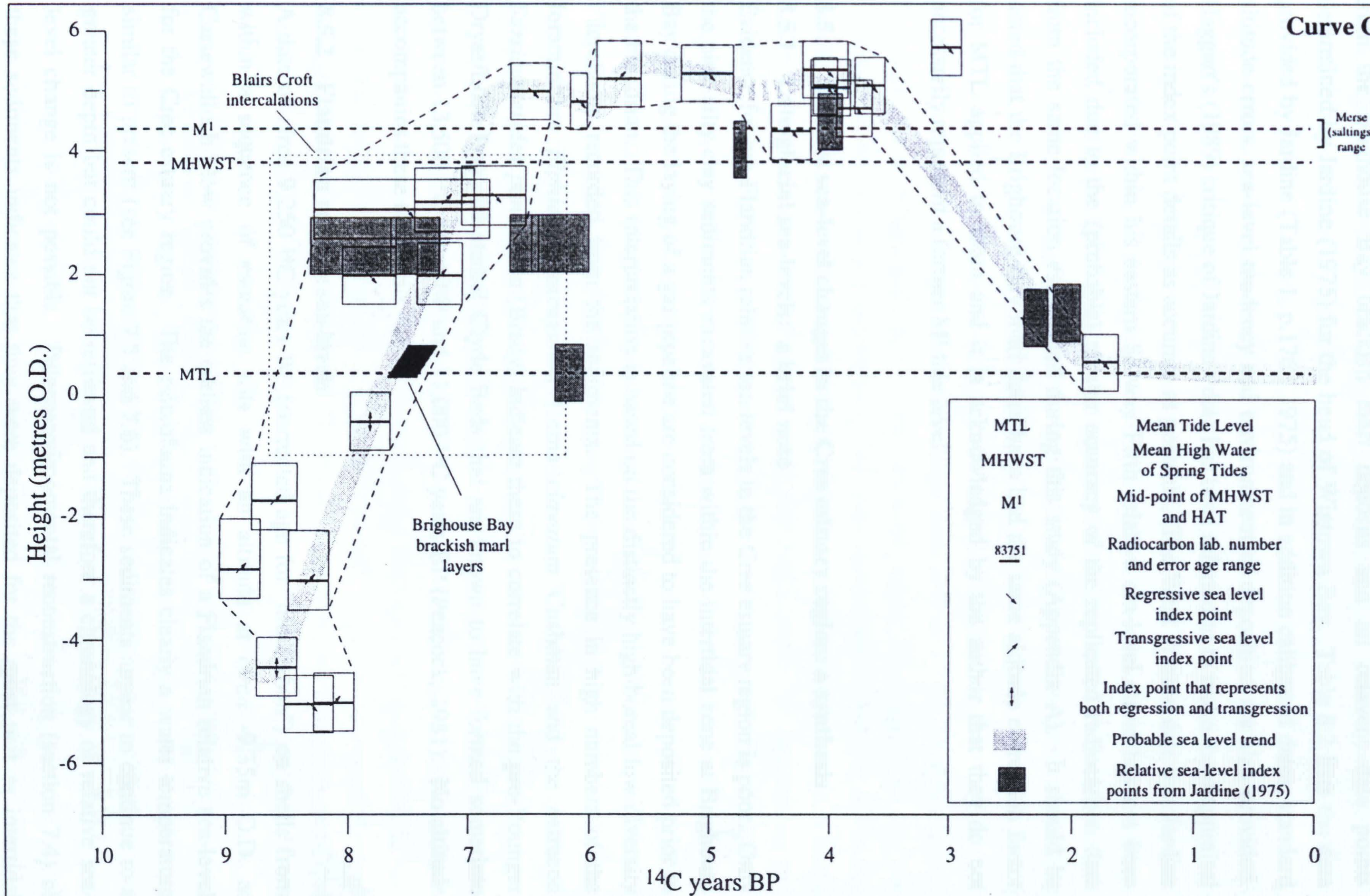


Figure 8.7 Relative sea-level band (Mean Tide Level) for the Cree estuary with altitude error magnitudes. Including index points from Brighouse Bay and West Preston, index points established by Jardine (1975) and also the timing and (possible) indicative altitude of the Brighouse Bay brackish marl layers (radiocarbon dates uncalibrated).

8.4.8 Mean Tide Level relative sea-level age-altitude graph: Curve G

Curve G (Figure 8.7) is essentially the same as curve E but it also includes the dates from the Brighouse Bay brackish marl deposits and all relavent data points determined by Jardine (1975) for the head of Wigtown Bay. Table 8.2 lists the data provided by Jardine (Table 1, p.176 - 1975) and in addition calibrated dates, standard altitude errors, sea-level tendency and environment of deposition are also provided. Haggart's (1989) critique of Jardine's data has been referred to to make the reappraisal of the index point details as accurate as possible. The West Preston date that Jardine incorporated within his eastern Solway Firth relative sea-level curve has not been included due to the (probable) greater accuracy of the replicated radiocarbon date from the same location established during this study (Appendix A). It should be noted that the Brighouse Bay marl dates have had the same altitude correction factor for MTL applied to them and it is acknowledged by the author that they do not necessarily represent a former M^1 tide level.

8.5 Relative sea-level changes in the Cree estuary region: a synthesis

8.5.1 Late-glacial sea-levels: a brief note

Evidence for pre-Flandrian relative sea-levels in the Cree estuary region is poor. Only the pink silty clay sediments excavated from within the intertidal zone at Brighouse Bay during the laying of a gas pipeline are considered to have been deposited prior to the Flandrian. This interpretation is based on the distinctly high-boreal low diversity microfauna recorded from the sediments. The presence in high numbers of the foraminifera *Elphidium excavatum* forma *clavatum* Cushman and the ostracod *Sarsicytheridea punctillata* (Brady) indicate these to correlate with the pre-Younger Dryas/Loch Lomond stadial Clyde Beds that are known to have formed sometime between 13,500 ^{14}C years BP and 11,000 ^{14}C years BP (Peacock, 1981). No altitude accompanies these deposits.

8.5.2 Flandrian relative sea-levels

A date of *circa* 9,250 ^{14}C years BP (corrected age for "old carbon") on shells from within a sequence of estuarine silts with an altitude at *circa* -9.35m O.D. at Carsewalloch Flow provides the earliest indication of a Flandrian relative sea-level for the Cree estuary region. The microfauna indicates clearly a water temperature similar to present (see Figure 7.5 and 7.6). These sediments appear to continue to a greater depth but could not be retrieved and therefore a chronology of relative sea-level change is not possible. Palaeoenvironmental reconstruction (section 7.4) of these sediments indicates that they were deposited for the most part as intertidal mudflats before shallowing to a vegetated saltings environment and eventually the development of a freshwater peat indicating a distinct negative tendency of relative sea-level from *circa* 0m O.D.. The timing of this regression is thought to be between *circa* 8,900 and 8,300 ^{14}C years BP.

Peats were also growing on the valley sides in additition to those that formed on the surface of the buried estuarine sediments. It is probable that the peats at the valley side began forming during the existence of the high sea-level that deposited the buried estuarine sediments. This can be inferred from the date of *circa* 9,600 ^{14}C year BP (Bishop and Coope, 1977) on the buried peat in the foreshore at Brighouse Bay which would have been forming at the same time as the relatively high sea-level of the early Flandrian.

Within this research no factor has been taken into account of the compaction and consolidation of minerogenic sediments. It would appear, however, from the low altitude (between *circa* -1.5 and -0.5m O.D.) of the buried peats overlying the buried estuarine sediments compared with those overlying the relatively solid substrate of the valley side (between *circa* 0.8 and 2.2m O.D.) that a degree of compaction has occurred. The thickness of the deposits in the Cree valley are certainly far greater than those recorded from Flandrian estuarine sequences elsewhere in Scotland where the compaction and consolidation of the fine grained estuarine minerogenic deposits has been considered negligible (e.g. Cullingford *et al.*, 1980). The consolidation of Flandrian estuarine muds by gravitational compaction has, however, been documented from a number of similar situations in both the British Isles and Europe (Skempton, 1970). The amount of compaction since deposition indicated by these case studies, by comparison, can account for the differential altitude of the buried peat layer that overlies both the buried estuarine sediments and hard rock of the valley side in the Cree estuary. A quantative assessment of the degree of compaction is not, however, within the scope of this study and can only be estimated through stratigraphical association of deposits. In doing so, however, the following advice of caution in any such assessment is regarded:

> "*It is potentially dangerous to assume, because peat seams in adjacent successions are horizontal, that the overall compaction can be ignored, unless there is strong support from a range of compatible data. It is also unwise to assess compaction over a wide area using arguments solely based on the correlation of the altitude, constitution and age of a peat seam or shell body*" (Greensmith and Tucker, 1986, p. 600).

Peat formation was eventually interrupted by a rising relative sea-level that inundated the Cree estuary valley once again and resulted in the further deposition of fine grained silts on top of the freshwater peats. The overlapping of radiocarbon-dated index points between the regressive contact of the buried estuarine deposits and this stratigraphically later transgressive phase makes the chronology of the two relative sea-level fluctuations difficult to constrain. Where the buried peat overlies the buried estuarine deposits at Palnure (see section 7.3) the timing of the regression and transgression phase is indicated as having taken place between *circa* 8,300 and 8,200 ^{14}C years BP. In a similar situation at Carsewalloch Flow the timing of the fluctuation is recorded by one date as occurring around *circa* 8,600 ^{14}C years BP. Where only a transgressive contact is recorded on the valley sides of the Cree (i.e. Blairs Croft and Carse of Clary) and also in the foreshore of Brighouse Bay the radiocarbon dated index points all indicate this event to have begun between *circa* 8,900 and 8,400 ^{14}C years BP. There is limited evidence in the palaeoecological reconstructions accross these sedimentary boundaries to suggest a depositional hiatus or erosive contact of the buried peats. What is certain is that a major relative sea-level fluctuation occurred during the time period between the maximal and minimal dates of 8,890±80 ^{14}C years BP and 8,190±80 ^{14}C years BP respectively. Thus by at least 8,000 ^{14}C years BP rising relative sea-levels had resulted in the extention of the Cree estuary up to the valley sides with silt deposition initiated.

In the central section of the Cree valley the stratigraphical evidence suggests that relative sea-levels appear to have continued rising until *circa* 4,000 ^{14}C years BP during which time the extensive blue/grey silts that comprise the carselands were deposited to a maximum altitude of *circa* 9.5m O.D.. Biostatigraphical investigations of these sediments from Carse of Clary (section 8.8), Carslae Cottage (section 7.6) and Carsewalloch Flow (section 7.4) all indicate that the relative sea-level rise during this time period was not uniform and that varying rates of relative sea-level rise can be distinguished. From these three locations there appears to exist a broadly synchronous lowering in the tidal regime in the upper half of each sequence (refer to Figure 7.26). It is possible that either a reduction in sediment supply to the estuary or a shifting river/estuary channel could be responsible for this apparent 'deepening' of the water body at this time. Alternatively, however, this change could represent an increased rate in relative sea-level rise. In borehole CWF/A the peak of maximum water depth (i.e. lowest point in the tdal regime) corresponds with the initiation of the Alder rise: a vegetational event which is dated at Brighouse Bay to *circa* 7,700 ^{14}C years BP and in the Cree estuary at Blairs Croft sometime between 7,800 and 7,200 ^{14}C years BP (see section 7.5.4). Perhaps not coincidentally the only recorded marine sediments from behind the fossil barrier at Brighouse Bay itself is constrained by this date and one of *circa* 7,500 ^{14}C years BP. The barrier at Brighouse Bay and the brackish water sediments behind it probably formed - at least initially - at the same time.

Carter *et al.* (1989) established that the development of coarse clastic barriers and their associated lagoons is controlled by a hierarchy of processes, embracing sea-level change, basement geometry, sediment supply, wave and tide regimes and textural parameters. In this they proposed that it was the rate rather than the magnitude of relative sea-level change which determines the evolution of coastal barrier and lagoonal coasts (Carter *et al.*, 1989). From the relative sea-level graph presented above (see Figure 8.7) it is clear that the brackish fossil-bearing marls from Brighouse Bay were deposited during the Main Postglacial Transgression when the rate of relative sea-level change was probably at its highest. It would appear here therefore that it was a high rate of relative sea-level rise that resulted in the change from silt deposition in the foreshore of Brighouse Bay to one of large clastic barrier construction. The apparently synchronous fall in the tidal regime of the estuarine sediments (indicating a relative sea-level rise) of the Cree provides some support to the suggestion that there was a distinctive change (i.e. increase) in the rate of sea level rise during the Main Postglacial Transgression.

By *circa* 4,000 ^{14}C years BP a regressive sea-level overlap is indicated by the freshwater peats that formed on the surface of the carselands at Carsewalloch Flow, Carsegowan Moss and the Moss of Cree. This may have continued until *circa* 3,700 ^{14}C years BP such as at Carsegowan Moss (section 7.7).

The relatively simple pattern of sea-level fluctuations in the Cree estuary during the Flandrian is, however, complicated by the geomorphological and stratigraphical evidence from outside the central area of the Cree carselands. At Palnure a radiocarbon date of *circa* 6,100 ^{14}C years BP on the surface (altitude *circa* 8.6m O.D.) of the carse sediments indicates that relative sea-level had fallen from this location by this time. Also the microfaunal evidence (section 7.3.1 and 7.3.2) throughout the sediments indicate that the greatest water depths at this site occurred in the lower half of the carse deposits. Jardine (1975) came to much the same conclusion for this location and also indicated that relative sea-level had fallen in the valley of the Palnure Burn by *circa* 6,400 ^{14}C years BP.

Further to the south of the Palnure Burn at Blairs Croft the carse sediments are recorded as interfingering with the valley side peats (see Figures 6.5 to 6.9). At BC/4/2 three of the most prominent intercalations are dated as occuring sometime between 7,800 and 7,200 ^{14}C years BP although overlapping radiocarbon dates (Beta-100916 to 100919) makes the differentiation of each event difficult. This complex sequence is further complicated by the barrier that extends out from the valley edge to the south of Blairs Croft in a northerly direction. The top of the carse sediments behind this feature are within a broad altitude range of *circa* 7.0-9.0m O.D. and have been dated at *circa* 6,800 ^{14}C BP (altitude *circa* 7.2m O.D.). No carse sediments have been shown to overly the barrier on its landward side. Outside the confines of the ridge on its seaward side the carse stratigraphically overlies the barrier that dips beneath the surface. As previously mentioned the date of the regressive contact of the carse surface at Carsewalloch Flow which is situated on the estuary side of the barrier is *circa* 4,000 ^{14}C BP.

No date has been ascertained for the formation of this barrier. However, from the evidence presented here it is suggested that barrier formation in the Cree estuary occurred during the later part of the Main Postglacial Transgression. It is possible that the barriers in the Cree estuary were deposited at a similar time to the Brighouse Bay barrier and, as such, may represent the shoreline formed as a result of a marked increase in the rate of relative sea-level rise that probably occurred after *circa* 7,500 ^{14}C years BP. This consequently allowed for the continued deposition of the carselands in the centre of the valley yet excluded estuarine sedimentation landward of the ridges. This interpretation is supported elsewhere on the western side of the valley from the carselands close to Baltersan Farm. Here a similar yet larger barrier extends from the valley side approximately eastwards into the Moss of Cree (see Figures 6.1 and 6.16). On the south side of this ridge the carse sediments overlie the ridge to a height of *circa* 9.8m O.D.. To the north of the ridge the altitude of the carse sediments have a height range somewhere between 8.0-8.5m O.D.. There is also clear evidence at Baltersan for intercalating carse and terrestrial peat sediments but it remains uncertain how these relate to ridge development if at all. The most distinctive of these is a peat layer that extends into the Moss of Cree at a consistent altitude of *circa* 5m O.D..

Outside of the probable (not proven) eastern limit of the Baltersan ridge on the Moss of Cree there is clear evidence of a layer of silt wedging to the north into peat (see Figure 6.17). Farther south this layer merges with the carse sediments. The carse surface is dated in this area to *circa* 6,500 ^{14}C years BP with the later and stratigraphically higher feature having been formed at sometime between 5,800 and 5,000 ^{14}C years BP. It is suggested that this layer represents a subtle Flandrian relative sea-level fluctuation that was constrained by the ridges at Baltersan and Blairs Croft and which was not large enough to overwhelm the carselands to the north of Baltersan, those of the Palnure Burn and north of Palnure. It is possible that the rate of peat formation to the north of the Baltersan was sufficient to have prevented the mid-Flandrian estuarine tides from swamping these areas. In the Forth Valley carselands a similar situation has been reported where rapid peat growth apparently excluded the high relative sea-levels of the Main Postglacial Transgression (Sissons and Smith, 1965). Evidence to support this hypothesis in the Cree estuary is limited as a result of subsequent peat cutting.

Following this mid-Flandrian sea-level fluctuation in the Cree estuary region relative sea-level must have fallen slightly to have again isolated the Moss of Cree at Baltersan by *circa* 5,000 ^{14}C years BP but to have allowed the continued deposition of the carselands to the south until *circa* 4,000 ^{14}C years BP.

Neither lithostratigraphical nor biostratigraphical evidence is present that might indicate a later sea-level oscillation between 5,000 and 4,000 ^{14}C years BP which may be responsible for the non-linear fall in relative sea-level over this time period. The clustering of sea-level index points between 4,300 and 3,700 ^{14}C years BP is nonetheless an interesting feature of the Cree estuary region sea-level history that may reflect an otherwise undetectable minor relative sea-level fluctuation. If this is the case then the later transgression could not penetrate past the point of the gravel ridges and across the Moss of Cree at Baltersan where the earlier shoreline exists.

It remains uncertain as to the rate of marine regression from the remaining carselands after *circa* 3,700 ^{14}C years BP. Evidence for a lower shoreline feature in the Cree estuary region is limited. The evidence from Crook of Baldoon (NX 445 528) and Hollanbank (NX 484 554), as presented by Jardine (1975), remains the only recognisable evidence for a late Flandrian relative sea-level in the Cree estuary region. Samples from these two locations have been dated to *circa* 2,000 ^{14}C years BP although these dates have been subsequently considered inaccurate (see Haggart, 1989). The blue/grey silts recorded in section from near West Preston Farm provide the most suitable opportunity to date the late Flandrian relative sea-level position. Palaeoecological analysis (see Appendix A) of the regressive contact (altitude 4.92m O.D.) of peat overlying estuarine silts (not recorded by Jardine, 1975) indicate that the change from marine to freshwater conditions was transitional and has been radiocarbon dated to *circa* 1,760 ^{14}C years BP. Whether these sediments represent a stage in the general fall of relative sea-level, a distinctive stabilisation phase in this regression or a late Flandrian shoreline deposited during a transgression of the sea can not be determined. What is certain is that after *circa* 1,760 ^{14}C years BP relative sea-level fell to present levels. In the Cree estuary region the uppermost shoreline feature of the modern estuary is that which delimits the merse.

On the basis of these findings presented in Figure 8.8 are a sequence of maps from different time periods that chart the probable evolution of the Cree estuary throughout the Flandrian. The channel of the Cree is simplified in the absence of detailed information about its shifting position through time. Similarly, a *circa* 2,000 ^{14}C years BP map is not provided due to the poor evidence for this time period in the Cree estuary.

8.5.3 A terminology for the Cree estuary region Flandrian estuarine sequence

If the above outlined interpretation of the sedimentary sequence as recorded in the Cree estuary region is accepted then a consistent terminology for this sequence is required. It is suggested here that the lowermost and consequently earliest of the Flandrian deposits that are known to extend lower than -9.4m O.D. from a maximum recorded altitude no greater than 0m O.D. are termed the Flandrian Cree estuary Deposits Unit 1(FCD/1).

The sediments formed between *circa* 8,500 and 6,400 ^{14}C years BP that represent the carse deposits are therefore termed the Flandrian Cree estuary Deposits Unit 2 (FCD/2). Clearly there is some difficulty in differentiating stratigraphically the carse from the deposits that were laid down during the mid-Flandrian fluctuation that culminated between 5,800 and 5,000 ^{14}C years BP but which appears [see alternative hypothesis outlined above] to have remained at a similar level until *circa* 4,000 ^{14}C years BP. Nonetheless that this relative sea-level fluctuation resulted in the deposition of the stratigraphically higher sediments is clear and these sediments are thus termed the Flandrian Cree estuary Deposits Unit 3 (FCD/3).

The relative sea-level fluctuations that are indicated by the intercalating silts and peat deposits at both Blairs Croft and Baltersan cannot be unequivocally related to regional positive and negative tendencies of sea-level. It is possible that the buried peat layer recorded at *circa* 5m O.D. at Baltersan correlates with a similar layer at Blairs Croft. If so then a regional relative sea-level fluctuation may be recorded but this interpretation remains only tentative.

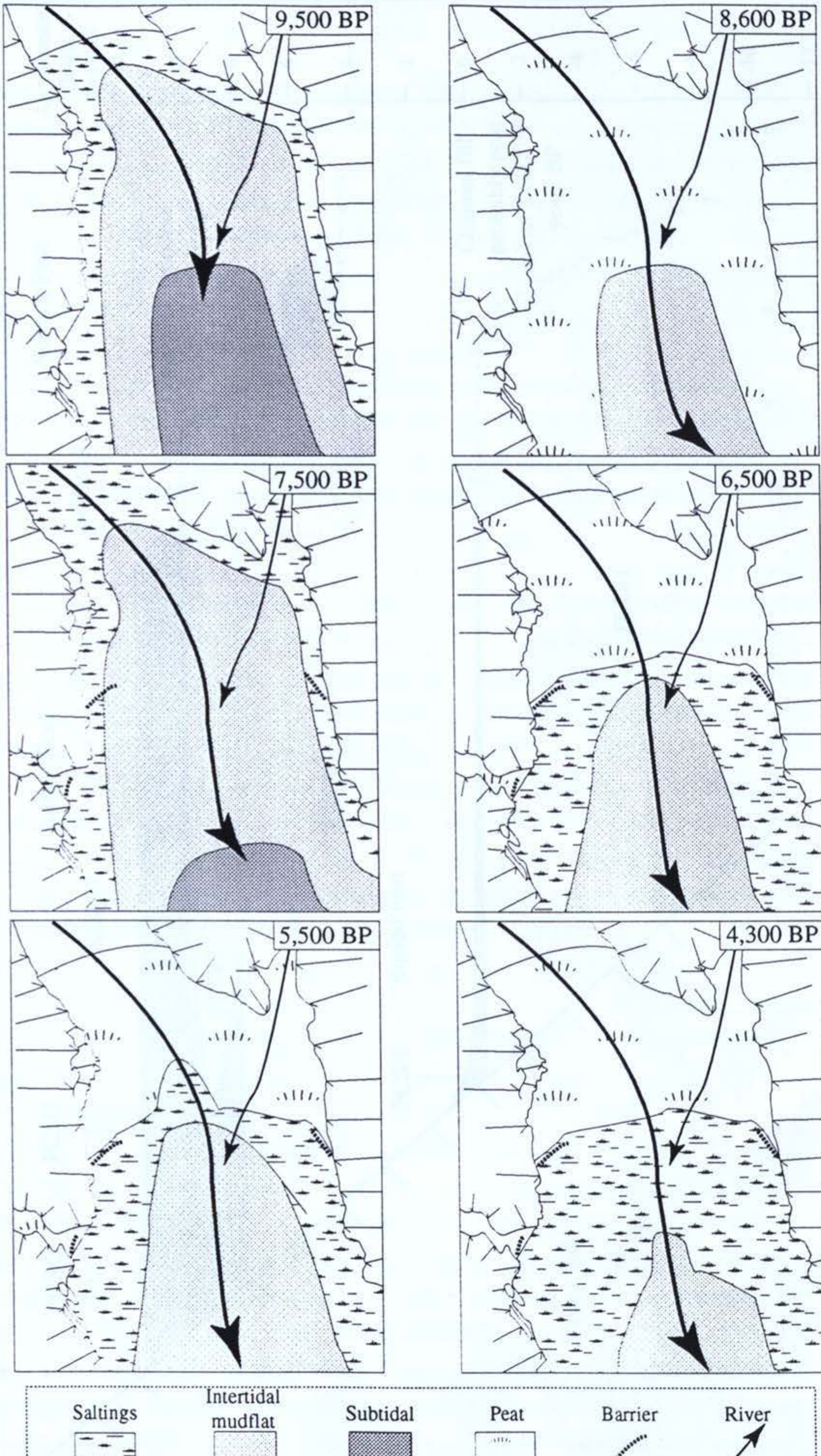


Figure 8.8 Flandrian evolutionary model for the Cree estuary

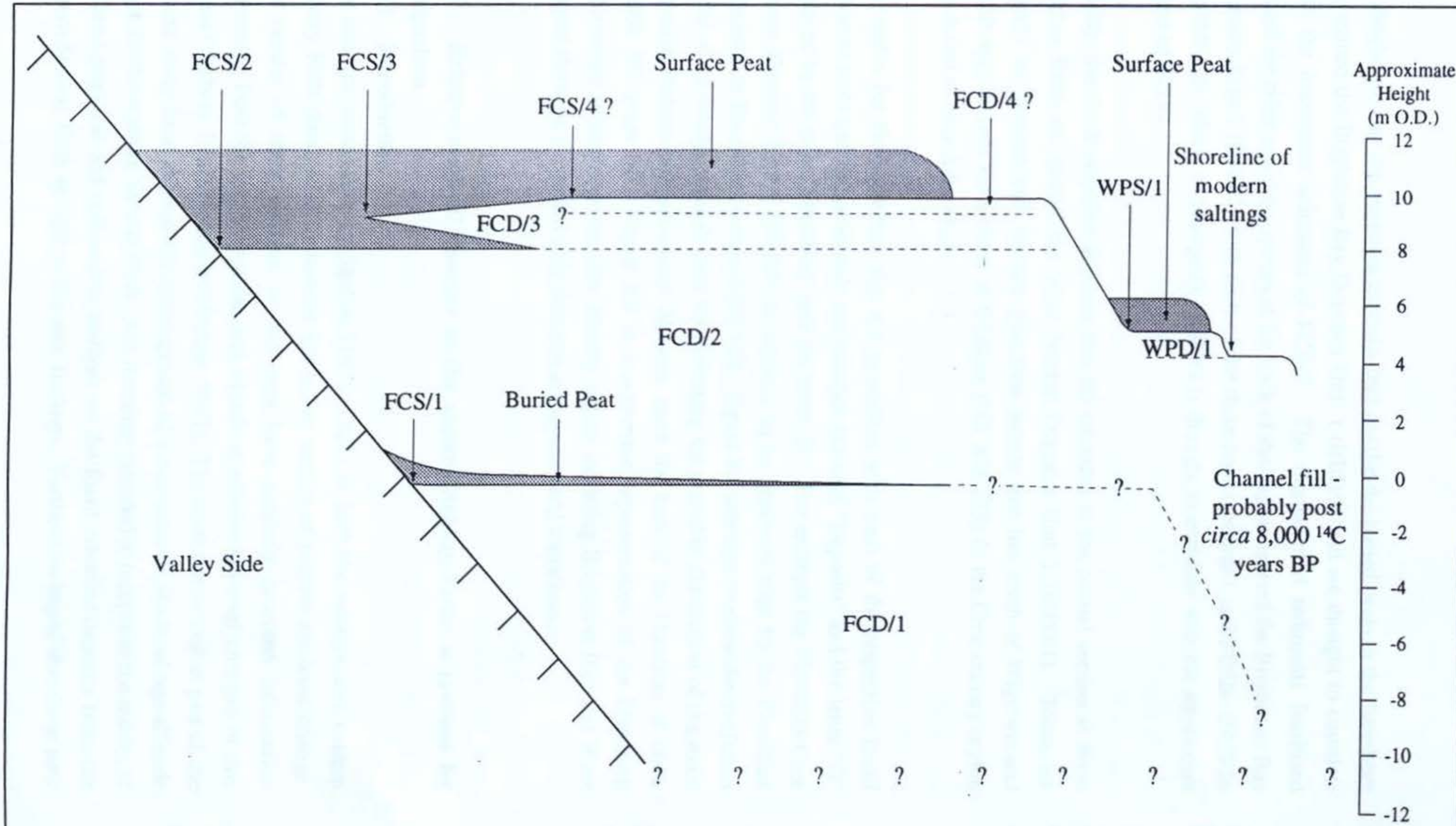


Figure 8.9 Schematic representation of the Flandrian sedimentary sequence in the Cree estuary region. For a full explanation of the codes see text.

At Brighouse Bay the estuarine deposits that overlie the buried peats in the foreshore are termed the Brighouse Bay Deposits Unit 1 (BBD/1) and are thought to correlate with the lowermost sediments of FCD/2. The marine marl sediments fossilised behind the ridge and dune system at the back of the bay are termed the Brighouse Bay Deposits Unit 2 (BBD/2) with each of the three layers recorded as BBD/2a, BBD/2b and BBD/2c (oldest to youngest). BBD/2 is thought to correlate with the uppermost layers of FCD/2.

Finally, the fossil estuarine deposits that are recorded in the coastal section at West Preston Farm are termed the West Preston Deposits Unit 1 (WPD/1). These are thought to correlate with the late Flandrian terrace that lies south of Wigtown and which may include the airfield at Baldoon (NX 435 535) in the Cree estuary region which lies at *circa* 5-6m O.D..

The codes for the shorelines that are associated with each of the respective fossil estuarine units use the same code and number but with "Deposits" and the letter "D" replaced by the term "Shoreline" and the letter "S". For example the Flandrian Cree estuary Deposits Unit 2 (FCD/2) is marked on its landward edge by the Flandrian Cree estuary Shoreline number 2 (FCS/2). Figure 8.8 attempts to show the evolution of the Cree estuary through time by indicating the probable distribution of the main shoreline features and associated deposits since the start of the Flandrian at *circa* 10,000 ^{14}C years BP. Figure 8.9 is a schematic representation of the Flandrian sedimentary sequence in the Cree estuary region including Brighouse Bay and West Preston showing the relationship between all deposits and shorelines.

8.6 Relative sea-level changes in the eastern Solway Firth: a revision by comparison

8.6.1 Introduction

The research undertaken by Jardine (1975, 1980) in both the western and eastern Solway Firth provided a framework for future studies of relative sea-level change. The results of other workers in this area have similarly provided information concerning both the late Devensian and Flandrian relative sea-level changes in this region (Nichols, 1967; Bishop and Coope, 1977). The results presented as part of the present study have allowed the development of a new relative sea-level age-altitude graph for the western Solway Firth. It is therefore intended to reappraise the results of the stratigraphical and radiocarbon analysis on the fossil estuarine deposits from the eastern Solway Firth in light of the new findings. Further it is hoped that these new insights will clarify the accuracy of the revised relative sea-level graph for the eastern Solway Firth as proposed by Haggart (1989).

8.6.2 Revision of the eastern Solway Firth relative sea-level data and interpretations

Evidence for the earliest Flandrian estuarine sediments to be deposited in the eastern Solway Firth is recorded at South Carse with a date of 9,390±130 ^{14}C years BP on peat sandwiched between estuarine deposits at an altitude of -1.05m O.D.. The lower of the estuarine sediments is recorded by Jardine (1975) as overlying a clay unit interpreted tentatively as till. The altitude of the peat layer is not constrained by a transect of boreholes so that an evaluation of whether it is of autochthonous or allochthonous origin is difficult. Clearly its altitude and position between estuarine sediments correlates well with the sequences recorded in the Cree estuary region and particularly at locations PAL/6 and CWF/A. If this relationship is accepted then the radiocarbon date at South Carse is probably anomalously old. Alternatively the buried peat may overlie an earlier shoreline to FCS/1, however, this is stratigraphically illogical. Whichever of these two suggested interpretations is accepted the use of this date as a relative sea-level index point is not advised. Nonetheless it is acknowledged that the early Flandrian buried estuarine sediments that correlate with FCD/1 and the relative sea-level fluctuation may well be recorded in the eastern Solway Firth.

Despite Late Devensian dates on organic remains in the section at Redkirk Point the earliest date that Jardine (1975) related directly to a former relative sea level is one of 8,135±150 ^{14}C years BP on an *in situ* tree stump (growth position) that is associated with a peat bed (variable altitude up to *circa* 5m O.D.) underlying the carse sediments. As has been previously detailed (see Chapter 2) the criticisms of the use of this date as a relative sea-level index point are many (Haggart, 1982; 1989). The more detailed description and interpretation of this section provided by Bishop and Coope (1977) led them to imply that a transgression of the sea had occured sometime after 10,300 ^{14}C years BP. This is based on two dates from a peat bed that underlies a highly disturbed and bedded unit of grey silts and fine sands - the provenance of these sediments were not however established. It is further inferred by Bishop and Coope (*op cit.*) that a relative sea-level fall ensued allowing the formation of the Peat 2 that underlies the carse sediments. The existence of a corresponding sedimentary unit to FCD/1 at Redkirk Point will remain unproven until the provenance of the sediments that lie between the Peats 1 and 2 are confirmed. If these sediments are proven to be estuarine or marine in origin then the timing of the transgression of the sea that deposited FCD/1 can possibly be inferred as having occurred by at least 10,300 ^{14}C years BP.

At Newbie Cottages three radiocarbon dates on peat underlying the carse deposits were used to record the timing of the transgression of the sea between *circa* 2m and 6m O.D. (Jardine, 1975). Despite a sequence of decreasing age with increased altitude Jardine ignored the oldest and lowest of these dates in his sea-level curve. It has been suggested from the palaeoenvironmental reconstructions in the Cree estuary region that there may have been a marked increase in the rate of relative sea-level rise at *circa* 7,500 ^{14}C years BP. It is therefore possible that the closeness in radiocarbon age of all three dates from Newbie Cottages between *circa* 7,550 and 7,250 ^{14}C years BP could reflect the same rapid inundation by sea water. Haggart (1982) in his revision of the sea-level curve index points duly noted that there was clear evidence for an increased rate of sea-level rise between *circa* 7,500 and 7,000 ^{14}C years BP.

For the radiocarbon date of *circa* 7,800 ^{14}C years BP on a peat layer sandwiched between estuarine deposits at Newbie Mains Haggarts's (1982) criticisms that the layer is not stratigraphically constrained and that the date relates to both a regressive and transgressive sea-level remain. However, if the peat layer is proven to be more extensive and that it does reflect a relative sea-level fluctuation at about this time then its altitude of *circa* 5m O.D. correlates well with peat beds between carse which have been recorded at a similar altitude at Baltersan Farm and Blairs Croft in the Cree estuary. The dates from the buried peat layers at Blairs Croft do overlap in age but nonetheless provide dates that correspond well with that of *circa* 7,800 ^{14}C years BP from Newbie Mains. No radiocarbon date has, as yet, been acquired from the Baltersan buried peat at *circa* 5m O.D..

The main difficulty with the four relative sea-level index points from Newbie Cottages and Newbie Mains is trying to account for the predating of the latter date with the former ones. Evidence in Racks Moss from boreholes undertaken by Nichols (Figure 3 in Nichols, 1967) record peat deposits underlying carse between 5-6m O.D.. A radiocarbon date on the contact between the carse and the buried peat at this location would most certainly provide an ideal opportunity to constrain the timing of this transgression more accurately.

Haggart (1982) notes that two seemingly suitable dates on the regressive contact of the carse from Netherlochar Woods and Midtown are ignored. The two dates are 6,645±120 ^{14}C years BP (altitude 9.15m O.D.) and 6,470±280 ^{14}C years BP (8.68m

O.D.) respectively. Haggart suggests that the differences in height between these index points and the best fit mean sea-level curve are associated with tidal differences caused by the configuration of the Lochar Gulf. The next regressive index point included by Jardine is from Newbie Cottages on allochthonous wood which inevitably has to be considered unsuitable as a relative sea-level point. More appropriate is the radiocarbon date on the peat overlying the carse at the same location which is dated as 4,290±100 ^{14}C years BP at an altitude of 8.18m O.D.. The explanation for the diachroneity of the contact at the different locations is suggested by Jardine to be as a result of the presence of a baymouth bar blocking the entrance to the Lochar Gulf. Haggart (1982) calls for the need for much more stratigraphic control before such a conclusion can be made. Further he suggests that the later date may simply relate to a stage in the general fall in sea-level from the maximum.

The above debate can probably be resolved using the comparative situation recorded in the western Solway Firth. As has been outlined above the stratigraphic and morphological evidence in the Cree estuary region and particularly at the Moss of Cree (near Baltersan Farm) where a minor fluctuation in sea-level between *circa* 6,500 and 5,000 ^{14}C years BP has been recorded which resulted in the deposition of FCD/3. The formation of barriers (spits?) across the estuary has not been related to this fluctuation but to a possible increased rate of relative sea-level rise at *circa* 7,500 ^{14}C years BP in the Cree estuary and, as mentioned above, is noted to possibly have occurred in the eastern Solway Firth between 7,500 BP and 7,000 ^{14}C years BP by Haggart (1982). Radiocarbon evidence implies that this later transgression did not penetrate as far as Palnure and the Palnure Burn in the Cree estuary. Therefore, it would appear that the same relative sea-level fluctuation occurred in the Lochar Gulf region resulting in an analogous pattern of deposition of a higher estuarine deposit. The exclusion of this later transgression from most of the Lochar Gulf is undoubtedly related in some way to the presence of the spits. As in the Cree estuary region it is possible that the rapid formation of peat in this region may have excluded any later marine inundation. The subtlety of the relative sea-level fluctuation makes its identification stratigraphically difficult as was proved in the Cree estuary. Indeed the impact of farming on the land in the eastern Solway may have removed any trace in the stratigraphical record of this event altogether.

Outside the limit of the barriers the presence of estuarine conditions appears to have continued until *circa* 4,000 ^{14}C years BP as was recorded in the Cree estuary region. Similar also is the absence of evidence that might suggest a sea-level oscillation between 5,000 and 4,000 ^{14}C years BP.

A late Flandrian terrace and shoreline have been identified as being relatively extensive in the eastern Solway Firth but the timing of relative sea-level regression from this altitude to the present is recorded from the West Preston location. The value of the dated sediments as a relative sea-level index point at this location has been critically analysed elsewhere (see Chapter 2 and Appendix A) and a new and more accurately constrained index point has been presented.

8.6.3 Summary

The above review has attempted to use the relative sea-level information revealed in this research as an analogue by which to compare and contrast the less detailed evidence from the eastern Solway Firth. It is not intended that these correlations should replace further litho- and bio-stratigraphical research in this area but, as has been shown, they have been used to aid the interpretations. In this way a more accurate model of Flandrian relative sea-level changes and coastal evolution in the eastern Solway Firth has been presented that can be tested through additional investigations. An additional benefit of this comparsion has been to show a marked similarity between the sedimentary sequences from the eastern Solway Firth and from the Cree estuary region. In the following chapter the Cree estuary region model of relative sea-level change is compared with similar results from the northern British Isles.

Chapter 9 Relative sea-level changes in the Cree estuary region: a discussion of the results in regional and global contexts

9.1 Introduction

In this chapter the results from the current investigation are compared with those from other regions. The inherent assumptions for a comparison of relative sea-level changes at a regional scale are that regional eustatic changes have acted uniformly and that former tidal ranges have been constant through time (Haggart, 1982). This acknowledges that any inter-regional variations in both the timing and consequently the altitude of fossil shorelines must reflect differential glacio-isostatic recovery. The Solway Firth is often considered to be towards the periphery of isostatic recovery in Scotland (e.g. Sissons, 1983) and it is probable that relative sea-level changes identified will reflect detailed regional changes in sea surface levels.

The limited data for Late Devensian relative sea-levels in the Cree estuary region does not allow for any meaningful correlation with other regions. Therefore, the emphasis of the following discussion is on placing the Flandrian relative sea-level history of the Cree estuary region into a wider context. This involves an inter-regional comparison of both the sedimentary sequences and also the relative sea-level chronology from the Cree estuary region with similar sequences elsewhere. These are primarily from Scotland but include also evidence from Northern Ireland and NW England - areas that are geographically close to the Solway Firth (for locations refer to Figure 2.2).

9.2 Relative sea-level changes in the Cree estuary region: a regional perspective

9.2.1 Introduction

In this investigation a number of distinctive Flandrian relative sea-level oscillations have been identified and an attempt is made here to establish the extent of these changes and identify whether they are more than just local phenomena. The following discussion has been divided up as follows: the early Flandrian (*circa* 10,000 to 8,500 ^{14}C years BP), the Main Postglacial Transgression (*circa* 8,500 to 6,000 ^{14}C years BP) and the mid to late Flandrian (*circa* 6,000 ^{14}C years BP to present).

9.2.2 Early Flandrian relative sea-levels in northern Britain

The evidence from the Cree estuary region does not reveal any impression of rising sea-levels in the early Flandrian. At the base of the recovered sediments a date of *circa* 9,700 ^{14}C years BP on shells that were deposited low in the intertidal zone of the proto-Cree estuary indicate that Mean Tide Level at this time was above *circa* -9.5m O.D.. Before the formation of a buried peat at *circa* -0.5m O.D. on the surface of these sediments the microfauna record that there was a clear shift to a saltings environment of deposition (i.e. close to an M^1 level) - probably indicating a falling relative sea-level. Buried peats overlying these sediments (termed FCD/1) and those which underlie stratigraphically younger estuarine sediments (FCD/2) indicate that a regression of the sea had occurred by *circa* 8,500 ^{14}C years BP (if not earlier) from the shoreline FCS/1 to an unknown minimum below *circa* -1m O.D..

This sequence of events for the early Flandrian in the Cree estuary region differs markedly from the evidence recorded on the east coast of Scotland. In the Forth valley (e.g. Sissons, 1967) and in Lower Strathearn (Cullingford *et al.*, 1980;1989) two shorelines are recorded for this time period and have been termed the Main and Low Buried Beaches. The timing of the relative sea-level regression that exposed the Main Buried Beach (surface of *circa* 11m and 3.2m O.D. in the Forth valley and Lower Strathearn respectively) has been dated as occurring by *circa* 9,600 ^{14}C years BP. No equivalent of this feature has been identified in the Cree estuary region. The timing of the regression from the Low Buried Beach in the Forth (surface at *circa* 9m O.D.) and Strathearn (surface at *circa* 2.8m O.D.), however, has been dated to *circa* 8,700 and 8,500 ^{14}C years BP respectively. This correlates well with the formation of the FCS/1 shoreline of the Cree estuary.

Although an equivalent of the Main Buried Beach has not been identified in the Cree estuary region in this study, it is possible that this is because the stratigraphic survey in this region was not broad enough to determine this higher feature. However, a number of widely spaced boreholes, close to the valley edge, did not establish any evidence for this feature. Furthermore, the date on the base (circa -9.5m O.D.) of the lowermost estuarine sediments that were recovered from the Cree estuary indicates that these were being deposited at about the same time as the formation of the Main Buried Beach in the Forth valley and Lower Strathearn.

It is suggested here that the Main Buried Beach equivalent should not neccesarily be expected to occur in the Cree estuary region. If the pattern of glacio-isostatic recovery in the early Flandrian involved a decrease in the rate of uplift from the centre of ice loading towards the periphery it is possible that a sequence of falling 'buried beaches' may be confined to those areas that lie much closer to the centre of isostatic recovery - such as the Forth valley and to a lesser extent Lower Strathearn. It would, therefore, be possible that the equivalent of the Main Buried Beach sediments in the Cree estuary region might be buried by the sediments that correlate with the Low Buried Beach. In other words the theoretical shoreline formed at the time of the Main Buried Beach in the Cree estuary region has been overlapped by the sediments deposited up to the time of the formation of the Low Buried Beach.

The whole issue is, however, thrown into confusion by evidence from two areas further to the north of the Forth and Strathearn locations in a region which is situated (apparently) in a similar Main Postglacial Shoreline isobase zone as the Cree estuary region (see Smith *et al.*, 1995). Haggart (1982) recorded a rapidly falling relative sea-level in the Moray Firth from *circa* 6.5 to 1.8m O.D. between *circa* 9,600 and 9,200 ^{14}C years BP down to an unknown minimum. The timing of this regression broadly correlates with the formation of the Main Buried Beach of the Forth and Lower Strathearn but there was no similar marked change in altitude of this feature in these two regions - only an apparently punctuated fall to the Low Buried Beach. No evidence of sediments that might correlate with Low Buried Beach are recorded from the Moray Firth region (see Haggart, 1982).

The problems of explaining this data are further exacerbated by evidence from the nearby Dornoch Firth (Smith *et al.*, 1992) where a date of *circa* 9,600 ^{14}C years BP is recorded for the regression from a buried estuarine deposit with a surface at *circa* -2m O.D.. The timing of this relative sea-level regression in the Dornoch Firth compares well with that for the Main Buried Beach in the Forth and Tay, yet the Dornoch Firth is in a broadly similar peripheral area to the Cree estuary and there is no recorded evidence for an overlapping later estuarine sediment (i.e. a Low Buried Beach equivalent).

In western Scotland the evidence for relative sea-levels in the early Flandrian is limited. At the Loch nan Eala sequence of isolation basins a sea-level minimum is recorded sometime between *circa* 10,000 and 8,750 ^{14}C years BP (Shennan *et al.*, 1993). Further to the south at Gruinart on the Isle of Islay a regression of relative sea-levels prior to *circa* 9,100 ^{14}C years BP is indicated (Dawson and Dawson, 1997). Rising sea-levels at this location are then suggested as having commenced by *circa* 8,800 ^{14}C years BP. Evidently a minimum of relative sea-levels probably occurred close to 9,000 ^{14}C years BP.

The above evidence has highlighted that some marked differences exist between the early Flandrian relative sea-level history of the Cree estuary region with those from E

Scotland. It is probable that the shoreline sequences in the different regions reflect the variability of local and regional tectono- and/or glacio- isostatic patterns. However, the pattern of relative sea-level change during the early Flandrian is only known for a few areas around the Scottish coast and until more studies are completed it is difficult to place the Cree estuary evidence in a wider context.

9.2.3 The Main Postglacial Transgression

Following the regression of relative sea-levels in the early Flandrian the initiation of the most pronounced of the Flandrian relative sea-level events occurred - the Main Postglacial Transgression. This was a high magnitude and rapid marine inundation that has been recorded in most relative sea-level records for the Flandrian of the British Isles. In the Cree estuary region evidence for the timing of the commencement of this event is somewhat confusing. Dates from stratigraphically comparable transgressive contacts place the initiation of this rise somewhere between *circa* 8,900 and 8,200 ^{14}C years BP. There is no clear evidence as to whether the age of this event changes with altitude or distance from the centre of isostatic uplift, and all that can be said is that if the youngest date (*circa* 8,200 ^{14}C years BP) is considered anomalously young then this transgression was probably initiated sometime between *circa* 8,900 and 8,400 ^{14}C years BP.

The timing of the commencement of the Main Postglacial Transgression recorded for the Cree estuary region correlates well with similar evidence from northern Britain. This is exemplified from the radiocarbon dates on the lowermost transgressive contacts of this relative sea-level rise from the Forth valley (*circa* 8,400 ^{14}C years BP; Sissons and Smith, 1965), Lower Strathearn (*circa* 8,500 ^{14}C years BP; Cullingford *et al.*, 1980; 1989), the Moray Firth (*circa* 8,200 ^{14}C years BP; Haggart, 1982), Loch nan Eala (*circa* 8,750 ^{14}C years BP; Shennan *et al.*, 1993), the Isle of Islay (*circa* 8,800 ^{14}C years BP; Dawson and Dawson, 1997), east and north coast of Northern Ireland (*circa* 8,400 and 8,150 ^{14}C years BP respectively; see Carter, 1982) and Morecambe Bay (*circa* 8,500 ^{14}C years BP; Zong and Tooley, 1996) which all indicate that, within the range of error of the methods employed, the timing of the commencement of this rise was broadly synchronous.

In the Cree estuary region the Main Postglacial Transgression rose to an apparent culmination at 9m O.D. by *circa* 6,500 ^{14}C years BP at which time relative sea-levels fell resulting in the formation of the Main Postglacial Shoreline (termed FCS/2 for the Cree estuary region). That the rate of relative sea-level rise was very high throughout this transgression is supported in comparable studies - even those closest to the centre of isostatic uplift (e.g. Forth valley - Sissons, 1967). It should be noted, however, that although the overall rate of this rise was relatively high, in the Cree valley microfaunal evidence from the sediments (FCD/2) associated with this rise indicate that the rate may have been variable.

The MPS in the Forth valley (confusingly termed PG1 - it is in fact the third postglacial shoreline in this area!) has been dated as forming by *circa* 6,800 ^{14}C years BP at an altitude of *circa* 15m O.D. (Sissons, 1982). In the Lower Strathearn area the formation of the MPS at *circa* 9.8m O.D. is dated as having formed by 6,300 ^{14}C years BP (Cullingford *et al.*, 1980; 1989). At Hole of Clien in the Tay valley the MPS, here at *circa* 10m O.D., is considered to have formed before *circa* 6,000 ^{14}C years BP (Smith *et al.*, 1985). At Waterside in the Ythan valley the date for the MPS as having formed before *circa* 4,000 ^{14}C years BP at *circa* 3.5m O.D. is considered anomalously young (Smith *et al.*, 1983). In the Philorth valley the evidence suggests that this shoreline formed at *circa* 1.5m O.D. sometime between *circa* 5,700 and 5,140 ^{14}C years BP (Smith *et al*, 1982). Further to the north in the Moray Firth the MPS, at an altitude of *circa* 9m O.D., has been indicated as forming sometime between 6,400 and 6,100 ^{14}C years BP (Haggart, 1982). In the Dornoch Firth, however, the timing of the regression from the MPS at *circa* 6m O.D. is considered anomalously young at *circa* 3,500 ^{14}C years BP (Smith *et al.*, 1992).

The evidence from elsewhere in Scotland for the formation of the MPS is more limited. In the Wick valley (NE Scotland) the culmination of the Main Postglacial Transgression and the formation of the MPS at *circa* 1.5m O.D. is considered to have occurred sometime between 6,800 and 5,900 ^{14}C years BP after which time sea-level regression was underway Dawson and Smith, 1997). At the Loch nan Eala (W Scotland) isolation basins no MPS can be identified (see Shennan *et al.*, 1994), however, it is considered here that a brief isolation at *circa* 6,600 ^{14}C years BP of the upper basin (lip at *circa* 6.3m O.D.) probably relates to the regression of relative sea-level following the culmination of the Main Postglacial Transgression. On Islay marine sedimentation apparently continued uninterrupted until a late Flandrian regression is recorded as late as *circa* 2,000 ^{14}C years BP at *circa* 4m O.D. (Dawson and Dawson, 1997). To the south of the Cree estuary region in north west England evidence that relative sea-levels were regressing by *circa* 6,800 ^{14}C years BP at *circa* -3m O.D. appears clear (Zong and Tooley, 1996).

The combined evidence outlined above, excluding the 'anomalous' dates, indicates that the culmination of the Main Postglacial Transgression in northern Britain occurred sometime between 6,800 and 6,000 ^{14}C years BP. The variability of the altitude of the MPS does not, however, combine with these dates to give any indication that a measureable diachroneity for the formation of this feature can be established with certainty. Indeed, the evidence from the most peripheral location to the centre of isostatic uplift, namely NW England, records one of the earliest "culmination" (i.e. regressive contact) dates at one of the lowest altitudes.

9.2.4 Mid to late Flandrian relative sea-level changes

Following the regression from the MPS in the Cree estuary region there is evidence for a younger sequence of sediments deposited both at higher and lower levels to those deposited during the Main Postglacial Transgression. A estuarine silt layer (FCD/3) at *circa* 9.1m O.D. has been dated as being deposited between 5,800 and 5,000 ^{14}C years BP and indicates that relative sea-level rose to a higher level than at the culmination of the Main Postglacial Transgression. Whether the relative sea-level regression resulted in the formation of FCS/3 shoreline shortly before *circa* 5,000 ^{14}C years BP is a local or regional negative sea-level tendency is uncertain. The regressive contact of an altitudinally higher (up to *circa* 9.6m O.D.) estuarine sediment (shoreline termed FCS/4) is dated to *circa* 4,000 ^{14}C years BP. This evidence may suggest that a later relative sea-level rise between the formation of FCS/3 and the regression from FCS/4 occurred. It could also be that the rate of terrestrial peat growth exceeded the rate of sea level rise and thus excluded the high relative sea-level from parts of the Cree estuary region. After *circa* 4,000 ^{14}C years BP relative sea-levels apparently fell dramatically when a lower estuarine sediment unit (WPD/1) was deposited at *circa* 4.9m O.D. until a regression to present levels shortly before *circa* 1,700 ^{14}C years BP.

In the Forth valley three lower shorelines below PG1 are recorded (termed PG2 to PG4) (Sissons, 1967). Of these the timing of regression from PG3 at *circa* 4,000 ^{14}C years BP according to Sissons' diagram (p. 185, Sissons, *op cit.*) appears to correlate well with FCS/4 of the Cree estuary. By inference it is possible to suggest that PG2 and PG4 correlate to FCS/3 and WPD/1 although the absence of any radiocarbon dates makes this only speculative.

Further to the north on the east coast of Scotland a date of *circa* 4,000 ^{14}C years BP on a regressive contact (*circa* 3.5 m O.D.) at Waterside in the Ythan valley was recorded (Smith *et al.*, 1983). This was considered by Smith *et al.* (*op cit.*) to be anomalously young for they considered the surface of the sediments to relate to the MPS. In light of the Cree estuary evidence it would now appear probable that at this location the regressive contact relates to the FCS/4 shoreline of the Cree estuary region. Also at this site there is some fragmentary evidence for lower terraces in the carse sediments indicating a younger fluctuation of relative sea-level, however, no date is provided for these (Smith *et al.*, *op cit.*). A similar situation is recorded in the Dornoch Firth where a date on a regressive contact at *circa* 3,500 ^{14}C years BP was again considered anomalously young (Smith *et al.*, 1992). Below this in the same general area fragments of another (younger) shoreline were identified but could not be dated (Smith *et al.*, *op cit.*). Of further interest in the Dornoch Firth is a possible increase of marine influence during the supposed general fall of relative sea-level at *circa* 1.9m O.D. by *circa* 1,900 ^{14}C years BP (Smith *et al.*, *op cit.*) which may correlate with the formation of WPS/1 in the Solway Firth.

In the Moray Firth regressive contacts from 8.9 to 8.7 m O.D. have been dated to *circa* 5,800 and 5,500 ^{14}C years BP respectively (Haggart, 1982). The timing of this regression can not be correlated with any such event in the Cree estuary region. A site at Moniack revealed a regressive contact that was dated to *circa* 4,760 ^{14}C years BP which was considered anomalous (Haggart, 1982) but which may indicate that a younger relative sea-level fluctuation is also present in this region. Elsewhere, in the Wick valley (NW Scotland) two later Flandrian transgressions at *circa* 4,500 to 4,350 ^{14}C years BP and from *circa* 1,200 ^{14}C years BP are recorded (Dawson and Smith, 1997). It is possible that the first of these may relate to the FCS/4 of the Cree estuary.

Evidence from the west coast of Scotland for mid to late Flandrian relative sea-level changes is poor. At Loch nan Eala a regressive contact from an isolation basin at *circa* 6.3m O.D. at about *circa* 4,000 ^{14}C years BP has been recorded (Shennan *et al.*, 1994). This relative sea-level fall may well correlate with the regression from FCS/4 in the Cree estuary region. Further to the south on the Isle of Islay estuarine sediments were deposited apparently uninterrupted for much of the Flandrian until *circa* 2,000 ^{14}C years BP when relative sea-levels are recorded as regressing (Dawson and Dawson, 1997). The striking similarity between this regressive date at that for WPS/1 in the Solway Firth may indicate that this relative sea-level fall was more than just a local phenomenon.

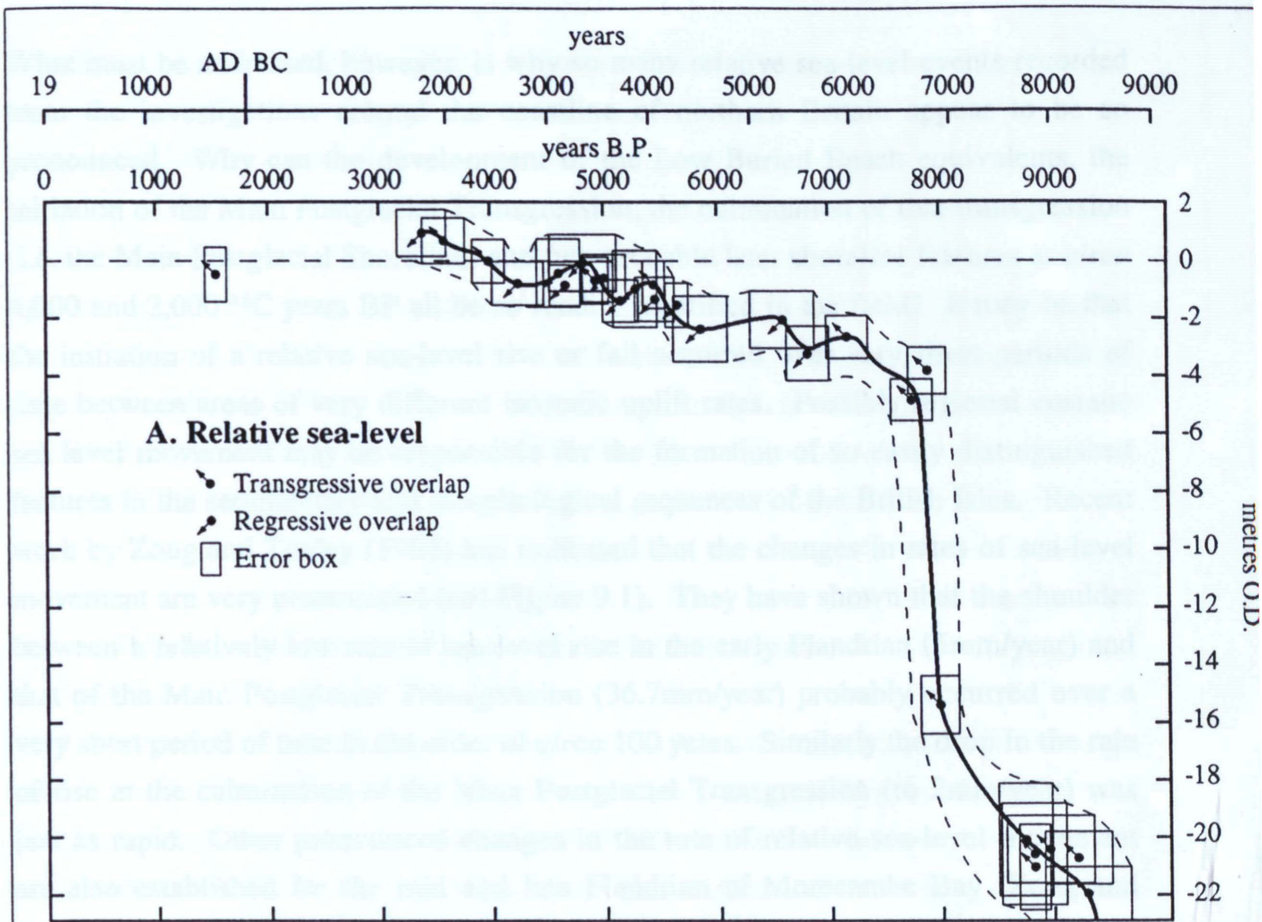
The evidence from Morecambe Bay in NW England to the south of the Solway Firth discloses a series of regressive and transgressive events in a complex sequence of intercalating estuarine and terrestrial sediments (Tooley, 1978; Zong and Tooley, 1996). Of particular interest is the rate of relative sea-level movement graph which indicates very clearly that in this area there were higher rates at *circa* 5,500 and 4,200

^{14}C years BP and falling rates at *circa* 5,400, 4,900 and after *circa* 3,500 ^{14}C years BP (Figure 9.1). None of these can be closely correlated with the relative sea-level changes recorded for the mid and late Flandrian of the Cree estuary region although some similarity in the timing of these changes and the Cree estuary region events is noticeable.

From this small body of evidence it is possible to suggest that there may well exist two very significant relative sea-level fluctuations in the late Flandrian at *circa* 4,000 ^{14}C years BP and *circa* 2,000 ^{14}C years BP respectively. Only by increasing the number of investigations in those areas towards the periphery of isostatic uplift will it be possible to support the existence of these features more confidently. The physical evidence indicates that in the mid to late Flandrian no eustatic rise ever apparently equalled the rate recorded for the Main Postglacial Transgression phenomenon. However, the presence of a number of younger marine sediment units that overlap the older "Main Postglacial Shoreline" sediments indicate that there were other times in the mid and late Flandrian where the rate of eustatic rise exceeded in places the rate of isostatic uplift. In the peripheral Cree estuary this has been registered as a clear overlap of younger sediments on top of the Main Postglacial Shoreline feature. Nearer the centre of uplift, such as in the Forth valley, these relative sea-level transgressions have been registered by a sequence of terraces formed as the general fall in relative sea-level in the late Flandrian was interrupted.

9.2.5 Discussion

It would appear from the above discussions that although distinguishable Flandrian shoreline sequences exist in the morphological and sedimentary records around the coastline of northern Britain there is no unequivocal evidence for shoreline diachroneity. It is probable that many of the difficulties stem from the innaccuracies of the radiocarbon dating proceedure - including sample selection. Where apparent evidence for diachroneity may have existed the new data from the Cree estuary region, and similar peripheral locations, has shown that overlapping shorelines from a later relative sea-level fluctuation can easily give the impression of shoreline diachroneity (e.g. Ythan valley and Dornoch Firth). These oscillations in relative sea-level can be so subtle that they may not leave any distinguishable signature in the sedimentary record and so can easily be overlooked or perhaps obliterated by subsequent anthropogenic activity. These problems must be tackled if a meaningful discussion on shoreline diachroneity is to take place for the shoreline sequence of the British Flandrian.



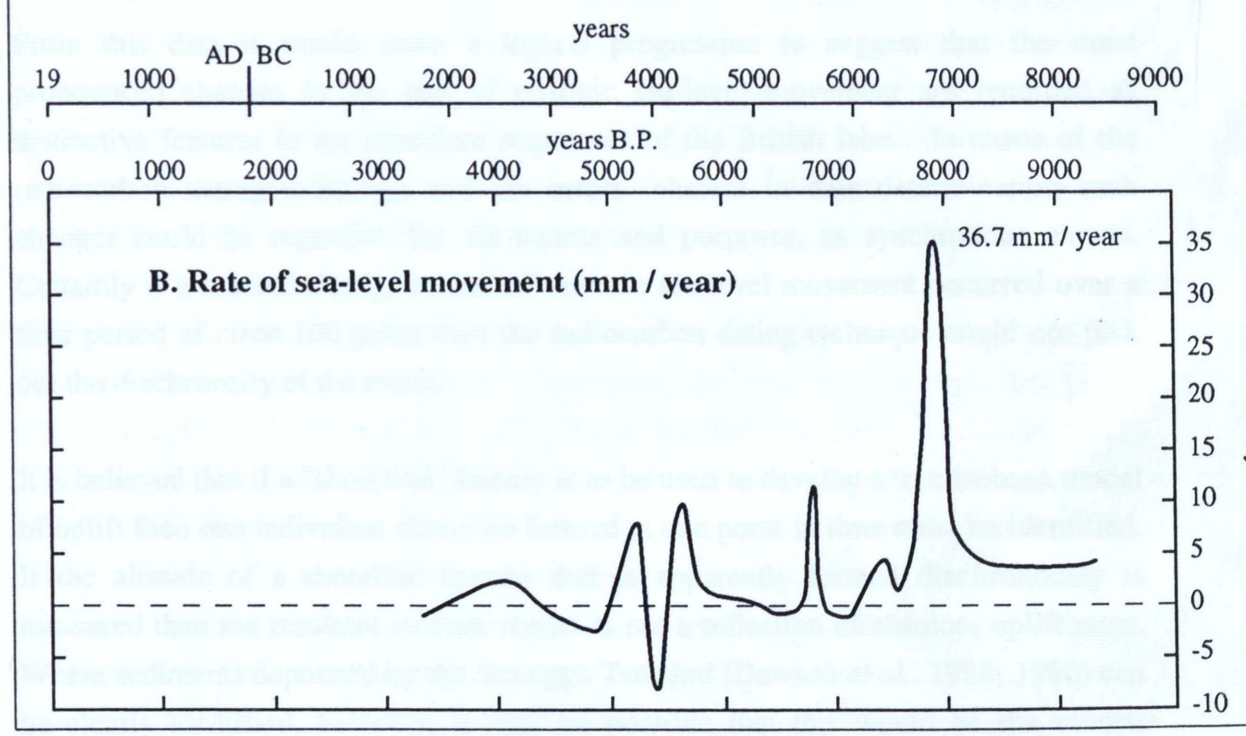


Figure 9.1 Relative sea-level band (A) and rate of sea-level movements (B) for Morecambe Ba
In diagram A, the dashed lines outline a narrow band within which a solid line is drawn throug
selected index points. Rates of sea-level movement (B) are calibrated and calculated in 50-yr
intervals on the basis of the sea-level curve from A (source Zong and Tooley, 1996).

What must be addressed, however, is why so many relative sea-level events recorded from the investigations around the coastline of northern Britain appear to be so pronounced. Why can the development of the Low Buried Beach equivalents, the initiation of the Main Postglacial Transgression, the culmination of that transgression (i.e. the Main Postglacial Shoreline) and two probable later shoreline features at *circa* 4,000 and 2,000 ^{14}C years BP all be so readily identified in the field? It may be that the initiation of a relative sea-level rise or fall occurred over very short periods of time between areas of very different isostatic uplift rates. Possibly regional eustatic sea level movement may be responsible for the formation of so easily distinguished features in the sedimentary and morphological sequences of the British Isles. Recent work by Zong and Tooley (1996) has indicated that the changes in rates of sea-level movement are very pronounced (see Figure 9.1). They have shown that the shoulder between a relatively low rate of sea-level rise in the early Flandrian (5mm/year) and that of the Main Postglacial Transgression (36.7mm/year) probably occurred over a very short period of time in the order of *circa* 100 years. Similarly the drop in the rate of rise at the culmination of the Main Postglacial Transgression (to 2mm/year) was just as rapid. Other pronounced changes in the rate of relative sea-level movement are also established for the mid and late Flandrian of Morecambe Bay (Zong and Tooley, *op cit.*)

From this data it would seem a logical progression to suggest that the most pronounced changes in the rate of eustatic sea-level movement are recorded as distinctive features in the shoreline sequences of the British Isles. In terms of the radiocarbon dating technique and the errors inherent in date determination such changes could be regarded, for all intents and purposes, as synchronous events. Certainly if a marked change in rate of eustatic sea-level movement occurred over a time period of *circa* 100 years then the radiocarbon dating technique could not pick out the diachroneity of the event.

It is believed that if a "shoreline" feature is to be used to develop a true isobase model of uplift then one individual shoreline formed at one point in time must be identified. If the altitude of a shoreline feature that is apparently formed diachronously is measured then the resultant isobase model is not a reflection of absolute uplift rates. Where sediments deposited by the Storegga Tsunami (Dawson *et al.*, 1988; 1990) can be clearly identified, however, it may be possible that this would be the closest relative sea-level research will ever approach to a single "shoreline" in the sedimentary and morphological sequences of Scotland. What is striking, however, is the similarity between the isobase model based on the Storegga tsunami deposit and that formed by the Main Postglacial Shoreline feature (Smith *et al.*, 1993, Figures 5 and 6). If one feature is formed instantaneously and the other diachronously then the altitudes of both features might be very different spatially.

This clear association of the uplift patterns recorded by the (synchronously formed) tsunami layer and the (diachronously formed) Main Postglacial Shoreline feature further supports the above suggestion that the change in the rate of eustatic sea-level movement at the culmination of the Main Postglacial Trangression was so pronounced as to have been registered over a period of time too short to have permitted diachroneity to be determined by the radiocarbon method.

9.3 Relative sea-level changes in the Cree estuary region: a global perspective

The concept of global eustasy has been very much in the academic wilderness in recent years. The common and somewhat predictable position taken by many sea-level workers is that geoidal factors together with regional variations of isostasy and tectonism prevent the identification of a global eustatic sea-level curve. The requirement to concentrate on regional relative sea-level changes such as has been undertaken in the present investigation is considered a priority. This necessity has perhaps overshadowed the likelihood that global correlations of relative sea-level changes, particularly during the Flandrian, may still display a certain degree of global synchroneity. It is, therefore, intended here to briefly review recent developments in understanding global sea level changes and evaluate how these may relate to the relative sea-level change evidence from the Cree estuary region.

Within the last decade, primarily as a result of the development of the AMS ^{14}C dating technique, new information concerning the possible existence of global meltwater pulses since *circa* 13,500 ^{14}C years BP has been established (e.g. Fairbanks, 1990; Chappell and Polach, 1991; Fairbanks *et al.*, 1992; Blanchon and Shaw, 1995; Bard *et al.*, 1996). This section will, therefore, attempt to establish whether there is any clear relationship between these events and the Flandrian relative sea-level changes as recorded in the Cree estuary region following the precedent set by Zong and Tooley (1996) for the Morecambe Bay sea-level history. For this exercise only the most distinctive and pronounced relative sea-level events can be considered.

In the Cree estuary region there are two relative sea-level change events that are distinguished by their magnitude and regional extent. The first is the rapid rise in sea-level that occurred sometime prior to *circa* 9,250 ^{14}C years BP that resulted in the deposition of FCD/1. The second is the possible marked increase in the rate of sea-level rise recorded between 7,500 and 7,000 ^{14}C years BP that was possibly responsible for a barrier beach and spit building phase in this estuarine region where otherwise fine grained sedimentation predominates.

The Barbados meltwater discharge curve records two distinctive pulses with peaks at 12,000 ^{14}C years BP (MWP-1A) and 9,500 ^{14}C years BP (MWP-1B) (Fairbanks *et al.*, 1992). A positive correlation for the latter of the two pulses is synchronously registered in an ice core (A-84) from the Agassiz Ice Cap (Ellesmere Island) that records a period of intense melting peaking at *circa* 9,500 ^{14}C years BP (Koerner and Fisher, 1990). The sea-level record from New Guinea that spans the interval from 11,000 ^{14}C years BP to 7,000 ^{14}C years BP further supports the existence and timing of the meltwater pulse events (Chappell and Polach, 1991). Evidence from the drowned *Acropora palmata* reefs in the Caribbean-Atlantic province have recorded three distinctive catastrophic, metre-scale rises in sea-level-rise events at 12,000 ^{14}C years BP (14,200 cal yrs. BP), 9,500 ^{14}C years BP (11.5 cal. yrs. BP) and 6,900 ^{14}C years BP (7,600 cal yrs. BP) (Blanchon and Shaw, 1995). Reef cores from the completely different tectonic and hydro-isostatic settings of Tahiti, Barbados and New Guinea were similarly analysed for evidence of rapid sea-level change (Bard *et al.*, 1996). Here the evidence recorded the two meltwater pulses at 12,000 ^{14}C years BP (14,000 cal yrs. BP) and the one between 9,500 and 9,000 ^{14}C years BP (11,500 - 11,000 cal yr. BP) but no trace of the *circa* 6,600 ^{14}C years BP (7,600 cal yrs. BP) event.

It is suggested here that a meltwater pulse, possibly MWP-1B that peaked at *circa* 9,500 ^{14}C years BP, was responsible for the early Flandrian rapid relative sea-level rise recorded from shoreline sequences in northern Britain. Similarly, the Main Postglacial Transgression may also relate to a global meltwater pulse, however, the timing of the one recorded at *circa* 6,900 ^{14}C years BP from the Caribbean-Atlantic does not correlate well with this event. It is possible that the differences in ages reflect the methodological problems of dating techniques. Nevertheless, the suggestion is made that there is a possible correlation between the most pronounced rapid relative sea-level rise events and global meltwater pulse phenomena during the Flandrian. Until the chronological framework in both fields of study is improved it will remain difficult to make accurate correlations.

Chapter 10 Conclusions

10.1 Introduction

In the preceeding chapters the evidence for coastal evolution and relative sea-level changes, primarily during the Flandrian, has been presented and discussed. By comparing and contrasting investigations from two very different locations - a small coastal embayment (Brighouse Bay) and a large estuarine valley (the Cree estuary) - a more detailed picture of relative sea-level changes has been established for the Cree estuary region. The necessary revision of the previous sea level investigations from this region has been rewarded by the development of new models of coastal evolution and relative sea-level changes for the Flandrian. Rather than contradicting the work of Jardine (1975) the present investigation has, in general, supported the previous results and allowed them to be placed in a new model of relative sea level changes in the Cree estuary region.

Through a detailed comparison of these results with those from both the eastern Solway Firth and the rest of Scotland and northern England it has been possible to show some distinctive similarities in regional sea-level histories. In this way it has been reasserted - after Haggart (1982) - that a measurable shoreline diachroneity between areas of differential isostatic uplift can not be positively confirmed.

The following sections detail the main conclusions of the investigations into relative sea-level changes in the Cree estuary region. This is followed by suggestions for future lines of research. In addition an assessment is made of the application of foraminifera and ostracod analyses to studies of coastal evolution and relative sea level changes.

10.2 Late Devensian sea-levels in the Solway Firth

The red silty clays with stones that were excavated from the foreshore at Brighouse Bay during the laying of a gas pipeline have been shown to have a Lateglacial boreo-arctic microfauna. These are possibly the equivalent of the Clyde Beds which are found elsewhere in Scotland (Peacock, 1975). This would be the first time that sediments of this age have been identified in the Solway Firth. The relationship between these sediments and the marine sediments of arctic provenance identified in the Rhins of Galloway (Brady *et al.*, 1874) remains unclear. The presence of Lateglacial marine sediments in the valley of the Cree estuary has yet to be established. Reworked fossil ostracods incorporated within the early Flandrian sediments of the Cree estuary suggest an arctic provenance. This evidence may imply either that the Lateglacial marine sediments have been reworked in the Cree estuary by Flandrian seas or that the reworked microfauna came from an offshore source and that Lateglacial sediments remain to be identified in this area.

10.3 Flandrian relative sea-level changes and coastal evolution in the Cree estuary region

In the Cree estuary region there is strong evidence for four distinct marine transgression and regression events during the Flandrian. One further relative sea-level fluctuation is postulated. The bio- and litho-stratigraphical investigations have also provided detailed information on the changing form and environmental conditions of both the Cree estuary and the small embayment at Brighouse Bay through time. The following is a chronological summary of relative sea-level changes and coastal evolution in the Cree estuary region throughout the Flandrian:

1) Relative sea-level rose rapidly from prior to *circa* 9,700 ^{14}C years BP from at least *circa* -9m O.D. to a maximum altitude of *circa* -0.5m O.D. sometime between *circa* 8,600 and 8,300 ^{14}C years BP. During this transgression estuarine sediments were deposited in the proto-Cree estuary. The precise extent of these deposits have not been confirmed in this investigation and consequently the position of the estuary channel can not be accurately determined.

2) A relative sea-level fall to at least *circa* -1.5m O.D. ensued allowing peat development on the former saltings surface. At this time the valley of the Cree estuary would have appeared similar to the present situation where peat beds exist on a former estuarine saltings surface.

3) The subsequent relative sea level rise - which is correlated here with the Main Postglacial Transgression - is recorded at numerous locations in the Cree estuary region including Brighouse Bay. Overlapping dates with the stratigraphically earlier fall provide uncertainty as to the timing of this rise which would appear to be underway shortly after 8,800 ^{14}C years BP in Brighouse Bay. It is possible, however, that this anomalously old index point relates to the final stages of an earlier transgression. Other index points indicate that the rising sea-levels had reached *circa* 2m O.D. after *circa* 8,600 ^{14}C years BP.

4) The Main Postglacial Transgression appears to have been rapid at first before the rate of sea-level rise stabilised prior to *circa* 7,600 ^{14}C years BP. The Cree estuary at this time would have filled the valley with an extensive saltings terrace extending up to the valley sides. Evidence indicates that the course of the estuary channel would have been broadly comparable with its present position.

5) Microfossil evidence from fossil estuarine sediments may indicate that by *circa* 7,600 ^{14}C years BP there was a marked increase in the rate of sea level rise. It is probable that this change in the Cree estuary itself resulted in the reduction in the area of the saltings and the extension of the unvegetated intertidal mudflats. Drawing on Jardine's (1975) evidence it is also suggested that the Palnure Burn was invaded at about this time. At Brighouse Bay the formation of a barrier system, behind which a brackish lagoonal pond developed, may also correlate with the same increased rate of sea-level rise at this time. Barrier systems have similarly been identified in the Cree estuary associated with the fine grained estuarine sediments and it has been hypothesised that these formed at the same time. No radiocarbon dates supporting this hypothesis have been obtained.

6) The culmination of the Main Postglacial Transgression probably occurred sometime between *circa* 6,800 and 6,100 ^{14}C years BP. The date of *circa* 6,500 ^{14}C years BP from the Moss of Cree at Baltersan is considered to be the most accurate date for the timing of this event. After this time estuarine waters were isolated from certain areas of the Cree valley that are partially delimited by the barrier systems. These include the areas to the north of the Moss of Cree at Baltersan and the Palnure Burn in the north-east (based on Jardine, 1975). It has been assumed that the Cree river channel remained in existance throughout this period and the isolation is therefore taken to correspond to a fall of relative sea-level. The maximum recorded altitude of the former saltings surface is *circa* 8.9m O.D. and is correlated here with the Main Postglacial Shoreline. At Blairs Croft the isolation surface is markedly lower (*circa* 7.2m O.D.) and older (*circa* 6,800 ^{14}C years BP) than the aforementioned locations. A large radiocarbon error combined with sediment compaction and consolidation can easily account for these inconsistancies. It is also possible, however, that this location was isolated from the estuarine waters earlier than the culmination of the Main Postglacial Transgression as a result of the development of a local barrier system.

7) The regression of the sea mentioned above was not so great as to prevent the continued deposition of estuarine sediments to a maximum altitude of *circa* 9.5m O.D. in the southern part of the Cree estuary probably until shortly after *circa* 4,000 ^{14}C years BP. There is, however, stratigraphical evidence at the northern-most end of the Moss of Cree (Baltersan) that suggests there was a subtle relative sea-level fluctuation between *circa* 5,800 and 5,000 ^{14}C years BP at an altitude of *circa* 9.2m O.D.. The action of more recent peat cutting and agricultural activity prevents the establishment of the extent and significance of this apparent oscillation.

8) Relative sea-level subsequently fell after *circa* 4,000 ^{14}C years BP forming the highest of the Flandrian estuarine shorelines in the Cree estuary region. It has been postulated, in the absence of any physical evidence, that between the regression dated at *circa* 5,000 ^{14}C years BP and the regression dated at *circa* 4,000 ^{14}C years BP there was an intermediate relative sea-level rise.

9) In the Cree estuary close to the open waters of Wigtown Bay shingle ridges are considered to correlate with a later sea-level oscillation at *circa* 2,000 ^{14}C years BP (based on Jardine, 1975). Intercalating marine/terrestrial sediments representing this fluctuation are not present in the Cree estuary region. Further to the East the regression of the sea at West Preston is marked by an saltings surface of *circa* 4.8m which has been dated to *circa* 1,700 ^{14}C years BP. After this time relative sea level is considered to have fallen resulting in the formation of the present saltings surface. In the Cree estuary this feature has been measured as lying between *circa* 4.0 and 4.5m O.D..

10.4 Proposals for further relative sea-level research

Advances have been made in determining the extent of evidence for Late Devensian and early Flandrian coastal evolution and relative sea-level changes in the Cree estuary region and the Solway Firth as a whole in this research. At Brighouse Bay the presence of a marine sediment that was deposited under much colder conditions than were present at any time in the Flandrian is unequivocal. The full thickness of Flandrian sediments of the Cree estuary region was certainly not realised within the current lithostratigraphic investigations. Clearly with more sophisticated coring systems the full sedimentary sequences of this region may be determined. This research could be complemented by biostratigraphical investigations on offshore sampled boreholes from Wigtown Bay that are held by the British Geological Survey.

In addition a re-investigation of the raised 'arctic' marine deposits in the vicinity of Stranraer as identified by Brady *et al.* in the last century would provide further evidence for this hitherto barren region for indicators of Lateglacial relative sea level changes.

Evidence of early Flandrian relative sea-levels in the Cree estuary region has been positively identified. An accurate chronology of the timing of an early Flandrian rise and fall of sea level prior to the Main Postglacial Transgression has been hampered by radiocarbon dates on the same stratigraphical context which overlap. These inconsistancies may represent the error margins inherent in radiocarbon dating or, alternatively, could reflect the difficulties of determining depositional lacunae using stratigraphical and palynological analyses. In order to resolve these anomalies it will be essential in future investigations to collect more samples for radiocarbon dating of this early Flandrian sea level oscillation.

The existence of relative sea-level fluctuations post-dating the Main Postglacial Transgression has been proposed drawing on the evidence from the Cree estuary region. This evidence is, however, far from widespread. Although there is scope for further research within the lower Cree valley it would also be appropriate to attempt a complete re-evaluation of the relative sea-level investigations from the eastern Solway Firth. In Chapter 8 the probability that these two areas display similar characteristics of Flandrian coastal evolution has been implied. A more detailed lithostratigraphical and geomorphological programme of research may reveal more clearly evidence for mid-Flandrian relative sea level fluctuations.

10.5 Foraminifera and ostracods in relative sea level research

The multidisciplinary nature of the research has provided a greater insight into changing coastal environments throughout the Flandrian. Where lithostratigraphic changes were not apparent the biostratigraphical investigations recorded a number of clear changes in the environment of depositon. Of all the techniques utilised in this investigation the insights into sea level changes and coastal evolution provided by foraminifera and ostracod analyses were unsurpassed.

Diatom analysis is commonly employed in investigations of relative sea-level change despite some clear advantages of foraminifera and ostracod analyses over this technique. Foraminifera assemblages particularly can be related directly with modern estuarine depositional environments and consequently a specific tide level. The complexities of taphonomic processes and environmental factors affecting diatom distribution conspire against the identification of a similar assemblage/depositional environment relationship (see Chapter 4). Where neither foraminifera nor ostracoda are preserved diatoms inevitably remain the most valubale palaeoecological tool for reconstructing salinity changes.

The biostratigraphical investigations in the Cree estuary region undertaken in this research have proved rewarding. Foraminifera analysis of the thick fossil estuarine muds has provided a detailed record of changing depositional environments which, by inference, have been correlated with fluctuations in relative sea-levels. In the investigations of the fossil marls at Brighouse Bay the foraminifera analysis again proved valuable, however, in this palaeoenvironment which fluctuated between brackish and freshwater deposition the benefits of ostracod analysis were far greater. The combination of the two techniques in determining the cold water provenance of the pink silty clays from Brighouse Bay further exemplified their strengths.

The modern survey of foraminifera and ostracod populations detailed in Chapter 4 illustrates clearly the variability of assemblage distributions between intertidal environments. In future a more comprehensive survey of contemporary microfaunal distributions could be undertaken from a variety of coastal environments. Such a survey would neccessarily incorporate detail of seasonal variability in population structure, water salinity, particle size analysis, sediment chemistry, vegetation and, where possible, associated micro- and macro-biota. Essentially this information should be related directly to a local tide level.

10.6 Overall conclusion

The main aim of this research was to establish the pattern and extent of Flandrian relative sea level movements for the Cree estuary region. Although there remain some inconsistancies in the data and uncertainties in their interpretation it is believed that this aim has been achieved. This has been possible through a multi-disciplinary approach that has applied effectively foraminifera and ostracod analyses to understanding coastal evolution and relative sea-level changes. A chronology of positive and negative sea level tendencies in the Cree estuary region has been set out within the constraints of modern radiocarbon dating margins of error. This chronology, in combination with altitude data which has been evaluated for degree of compaction and consolidation of sediment, has been used to construct an age-altitude relative sea-level graph for the Cree estuary region.

The formation of a sequence of shoreline features in the Flandrian sedimentary sequence of the Cree estuary region probably relates to culminations in periods of relative sea-level rise. These are thought to have occurred by 8,500, 6,500, 5,000, 4,000 and 1,800 ^{14}C years BP. Correlation with other coastal sequences in the northern British Isles has shown that components of this chronology appear to be more widespread that was previously thought. It has been speculated that the similarity in the timing of some of these shoreline features relates to periods during the Flandrian when rates of eustatic sea-level rise were pulsed. It is this relationship, between eustatic and regional relative sea-levels, that will require more attention in future studies of sea-level change.

Appendix A

West Preston (Preston Merse)

A.1 Introduction and background information

A.1.1 Site and situation

Preston Merse lies *circa* 20km to the south of Dumfries (Figure A.1) and is a triangular area of relatively flat land (*circa* 7m O.D.) that is delimited by a break of slope on the northern side that runs between Caulkerbush (NX 928 574) and Southerness (NX 976 544). The shoreline on the southern side and the course of the Caulkerbush Burn to the west comprise the other two sides of the triangle. Sand dunes probably covered the whole of this area up to the break of slope but as a result of recent reclamation for pastoral farmland the dunes that are now incorporated into the Southerness Golf course are all that remain. Along the seaward edge of Preston Merse at a point just above MHWST a single line of the sand dunes has remained untouched to protect the farmland from the elements and unusually high tides. Conifer plantations cover a small part of the western end near to Mersehead Farm (NX 926 560).

A.1.2 Previous sea level studies

As outlined in section 2.4.4 Jardine (1975) identified peat deposits underlying the dune sands and overlying unfossiliferous (but presumed marine) sands (junction at 5.25m O.D.) in a section (NX 952 553) on the seaward side of the protective sand dune southwest of West Preston Farm. A radiocarbon date of 1,850±95 ^{14}C years BP on the peat (5cm thick slice) immediately overlying the sands was used to indicate a local marine regression at this time. Jardine (*op cit.*) inferred that the presence of this feature represented a pause in marine regression at *circa* 2,000 ^{14}C years BP prior to a relative drop of sea-level of approximately 1m to the present.

A.2 Present investigation

A.2.1 Introduction

Preston Merse is situated *circa* 35km from the Cree estuary area that is the focus of the current investigations. For this reason the data presented here has not been incorporated into the main part of the thesis. However, although there is evidence for a lower fossil shoreline in the Cree estuary (Jardine, 1975) at no point are there organic deposits overlying these features. Radiocarbon dates between *circa* 2,000 and 2,300 ^{14}C years BP (Jardine, 1975) on shells from fossilised ridges at Crook of Baldoon (NX 440 530) and Hollanbank (NX 482 555) give an indication that a lower

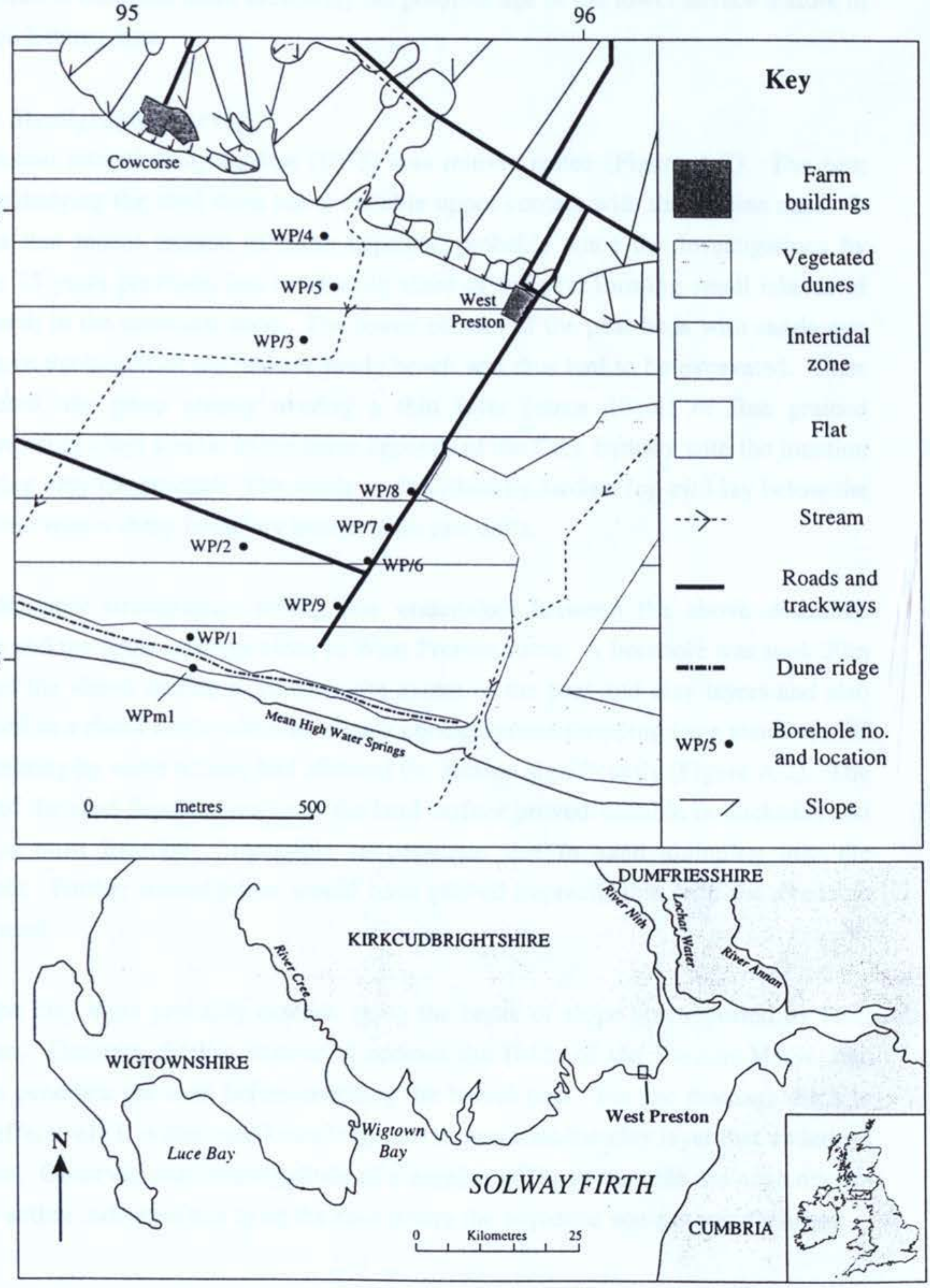


Figure A.1 West Preston Farm: Site location map, geomorphological map and borehole locations feature could have been formed by this time. The decision to reinvestigate the West Preston section was made in order to confirm and develop Jardine's investigations and in addition to establish more accurately the possible age of the lower terrace feature in the Cree Estuary area.

A.2.2 Stratigraphic survey

The section refered to by Jardine (1975) was reinvestigated (Figure A.2). The peat layer underlying the sand dune has a variable upper contact with the aeolian sand. It appears that recent erosion of these deposits, probably since the investigations by Jardine 25 years previous, has resulted in slabs of the peat forming small islands of salt marsh in the intertidal zone. The lower contact of the peat beds with sands was not above the height of the present sandy beach and thus had to be excavated. Once uncovered, the peats clearly overlay a thin layer (*circa* 10cm) of fine grained blue/grey silty clays similar to the carse deposits of the Cree Estuary with the junction appearing very transitional. The sands as described by Jardine (*op cit.*) lay below the silty clays with a sharp boundary between the two units.

A preliminary stratigraphic survey was undertaken between the above described section and the break of slope close to West Preston Farm. A borehole was sunk 20m north of the above section to confirm the extent of the peat and clay layers and also was used as a check on the altitude of each contact incase slumping (as a result of cliff undermining by wave action) had affected the section significantly (Figure A.2). The depth of the sand deposits that form the land surface proved variable in thickness and were at most locations impossible to penetrate due to sand slumping into the borehole. Further investigation would have proved impracticable with the available equipment.

That the clay layer probably extends up to the break of slope was reported by farm workers. Drainage ditches excavated accross the fields of the Preston Merse area always penetrate the sand before reaching the buried peat. For the drainage ditch to work effectively it is common knowledge not to penetrate the clay layer that underlays the peat. Observational investigations of a number of the accessable drainage ditches by the author indicated this to be the case where the sequence was not too disturbed.

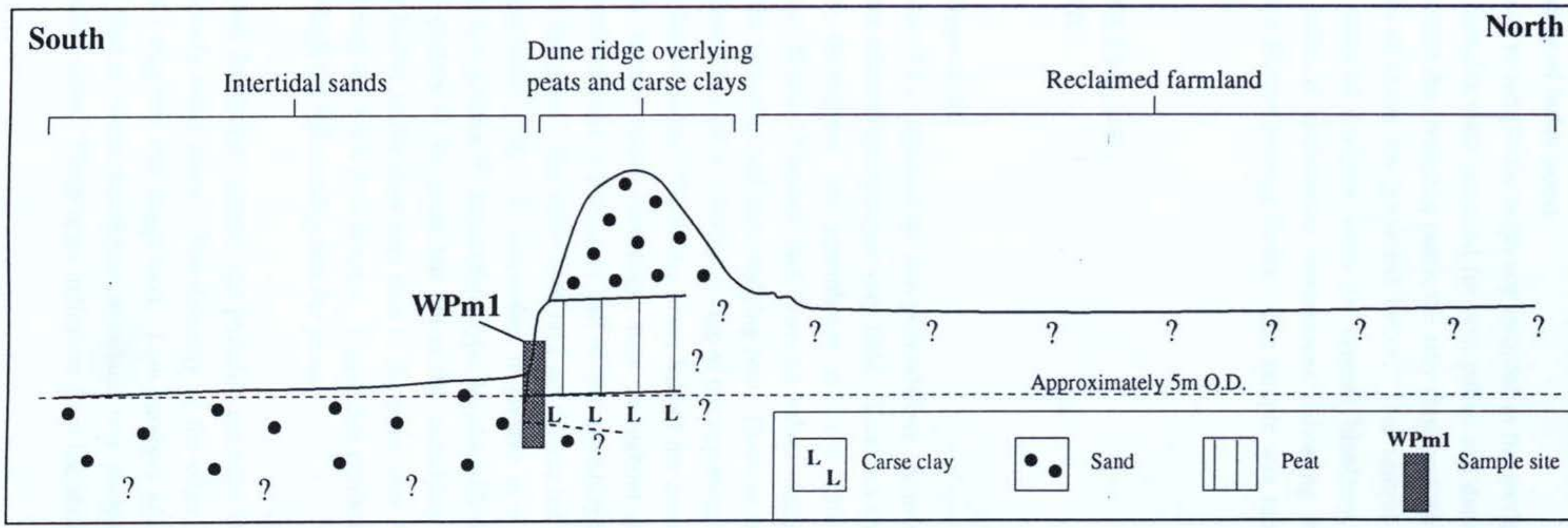


Figure A.2 West Preston: Schematic cross-section through the sample site

A.2.2 Determination of index point

A monolith was used to sample the sequence recorded in the section in the foreshore at West Preston. Samples were prepared for both pollen and diatom analysis across the boundaries between the overlying peats, the silty clays and the underlying coarse sands. The results of these are presented below. One sample was prepared for foraminifera and ostracod analyses from the organic blue/grey silty clays which contained a few tests of *Jadammina macrescens* indicating that the sediments probably represent a former saltings facies. One sample was subsequently sent for radiocarbon dating.

WP monolith 1 (NX 9520 5497)
Altitude: 4.99m O.D.
Depth: 0-30cm

Pollen analysis (Figure A.3)

The sands at the base of the sequence are non-polleniferous. Across the silty clay/peat boundary the pollen assemblage changes very little. Tree and shrub values remain relatively constant throughout the assemblage at *circa* 25% and *circa* 10% respectively. *Alnus*, *Betula*, *Fraxinus* and Coryloid values change little across the junction between the silty clay and the overlying peat. *Quercus* values do, however, increase steadily from *circa* 5% to 15% by the top of the sequence. Numbers of *Pinus* pollen are slightly higher (*circa* 2%) in the lower half of the assemblage than in the upper half. Herb values remain constantly high throughout at *circa* 60% with Cyperaceae the dominant taxa in the lower half of the assemblage switching to high Poacaeae values in the peats. The other herb taxa are diverse but are all recorded in low numbers at generally <1% - *P. lanceolata* is present in a number of levels. Aquatics including *Sparganium/T. angustifolia* type, *M. alterniflorum* and particularly *T. latifolia* are all present in the peats but not in the underlying sediments. Spore values are slightly higher in the silty clay than in the peats with *Pteridium*, Filicales and *Polypodium* being the main taxa present. Finally the numbers of Indeterminate grains are initially high but fall steadily into the peats.

This sedge and grass dominated assemblage probably indicates that deforestation in this region has already taken place. The diversity of the other herbs including *P. lanceolata* certainly supports this suggestion. Low numbers of arboreal taxa does, however, suggest that a mixed deciduous woodland was present in the vicinity - probably on the valley sides. There is no indication from the above described pollen

Figure A1.3 West Preston: Percentage pollen diagram

Monolith: WPm1
Grid ref.: NX 9520 5497
Height: 4.99m O.D.

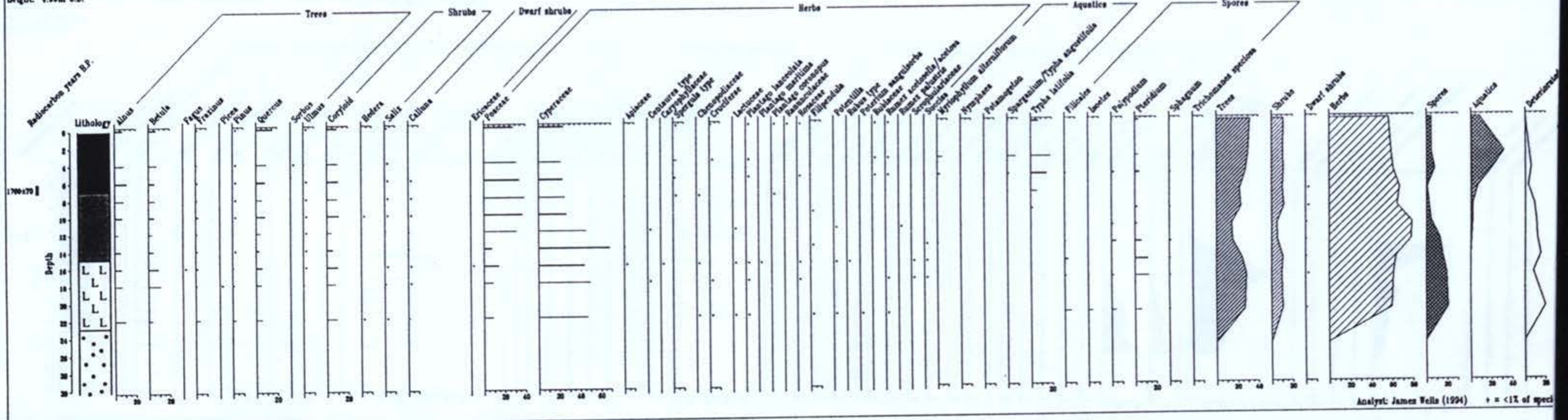
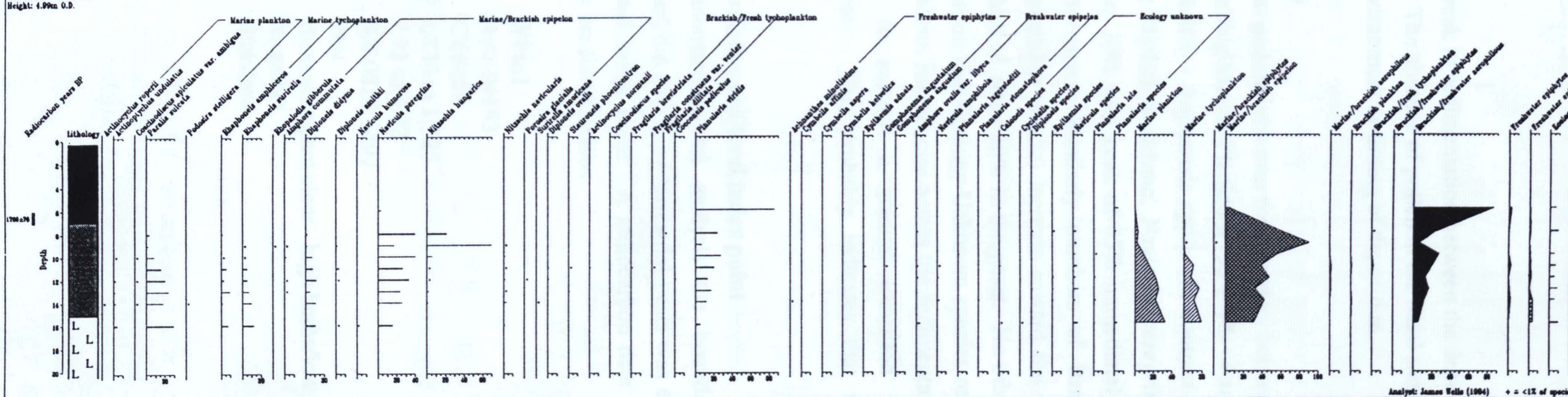


Figure A1.4 West Preston (monolith): Diatom percentage diagram

Monolith: WPm1
Grid ref.: NX 9520 5497
Height: 4.99m O.D.



assemblage that there was a break in sedimentation between the deposition of the silty clays and the overlying peats. The absence of pollen in the basal sands does not allow for an interpretation of the environment or timing of deposition.

Diatom analysis (Figure A.4)

The overall trend of the diatom populations over the boundary between the lower silty clays and the peats is one of falling Marine Planktons (30%-0% - *Paralia sulcata*) and Marine Tychoplanktons (17%-0% - *Raphoneis* spp.). In contrast Marine/Brackish Epipelon species - including *Diploneis didyma*, *Navicula peregrina* and *Nitzschia hungarica* - initially rise from 30% to a peak of 85% immediately below the peat before falling to 5% in the peat. Similarly numbers of Brackish/Freshwater Aerophilous species (i.e. *Pinnularia viridis*) increase toward the uppermost levels rising from 5% in the silty clays to *circa* 80% in the peats. No other lifeform group exceeds 5% of the total poulation and Ecology Unknown species remain at *circa* 5% throughout. The changing diatom frequencies across the sedimentary boundary from silty clay to peat appear to suggest a gradual transition from marine to brackish/freshwater deposition. This probably indicates that there was not a depositional lacuna.

A.2.3 Radiocarbon dated relative sea level index point

As a result of the palaeoenvironmental analysis the boundary between the brackish/marine sediments and the overlying terrestrial peats was evaluated as being suitable as a relative sea-level index point. A radiocarbon date was subsequently acquired of which full details are listed below.

Site code	WPm1
Laboratory code	Beta-84193
^{14}C date (years BP)	1760±70
Age cal. years BP (2 sigma)	1,830 to 1,525
Altitude (m O.D.)	4.93 to 4.92
National Grid Ref.	NX 9520 5497
Material	Peat
Environment	Human impact clear - high herbs/low trees and shrubs
Sea-level tendency	Negative
^{14}C procedure	Standard

A.3 Conclusion

It has been shown in this study that the sedimentary sequence recorded by Jardine (1975) for this location is more complex than previously thought. The newly identified blue/grey silty clays that underlie the freshwater buried peat have been shown to have been deposited under brackish/marine conditions - possibly as a vegetated saltings terrace. Pollen analysis indicates that the transition from brackish to freshwater conditions was probably uninterrupted. A radiocarbon date of 1,760±70 ^{14}C years BP on this boundary supports both the pollen evidence, which indicates that anthropogenic deforestation had already taken place at this location, and the radiocarbon date from the base of the same buried peat acquired by Jardine (1975). These combined results mean that the radiocarbon date is suitable as a relative sea level index point. This index point has been utilised in the Cree Estuary region age-altitude relative sea level graph in Chapter 8 of this thesis.

A.5 Borehole/monolith records for West Preston

West Preston (WP)
WP monolith 1 (NX 9520 5497)
4.99m O.D.

0-7	Compact well humified dark brown peat (with fibres and Phragmites)
7-10	Brown/grey silty peat
10-15	Brown/grey organic silty clay (with Phragmites)
15-23	Blue/grey silty clay (with Phragmites)
23-30+	Yellow/orange coarse/medium sand

WP 1 (NX 9513 5505)
7.79m O.D.

0-209	Sand (aeolian)
209-287	Dark brown/black well humified peat with wood and Phragmites
287-300	Dark grey/brown oranic silt with Phragmites
300+	Blue/grey medium/coarse sand

WP 2 (NX 9526 5526)
8.19m O.D.

0-360+	Sand (aeolian)

WP 3 (NX 9538 5571)
9.56m O.D.

0-29	Coarse sand (aeolian) with some organic content
29-64	Dark brown well humified peat
64-88	Banded organic coarse sand
88-101	Coarse sand

101-186	Dark brown/black well humified peat with fibres, wood, roots and <u>Phragmites</u>
186-193	Peat as above with sandy inclusions
193-215	Very organic coarse sand
215-400+	Coarse grey/yellow sand

WP 4 (NX 9543 5594)
10.62m O.D.

0-35	Sandy top soil
35-46	Peaty top soil
46-260+	Sand

WP 5 (NX 9545 5583)
10.01m O.D.

0-24	Very organic sandy top soil
24-46	Medium brown peat with fine sandy inclusions
46-70	Medium brown well humified silty sandy peat
70-75	Dark brown/black well humified compact peat
75-200+	Coarse sand

WP 6 (NX 9551 5525)
7.16m O.D.

0-25	Black well humified peat
25-30	Dark brown well humified fibrous peat with sandy inclusions
30-68	Light grey medium/coarse sand
68-70	Dark brown well humified peat
70-73	Light grey coarse sand
73-104	Dark brown well humified peat
104-123	Brown well humified very organic silt and sand
123-133+	Blue/grey fine/medium sand

WP 7 (NX 9557 5529)
7.56m O.D.

0-5	Yellow sand (aeolian)
5-27	Dark brown well humified peat with fibres
27-50+	Light grey/brown medium coarse sand with organics and wood

WP 8 (NX 9563 5537)
8.30m O.D.

0-13	Mixed sand (trench contamination)
13-45	Dark brown well humified peat with fibres (sandy inclusions at 41-45)
45-57+	Medium/coarse sand

WP 9 (NX 9545 5512)
6.93m O.D.

0-52	Yellow sand
52-66	Dark brown well humified peat with sandy inclusions
66-75+	Very light grey sand

Appendix B
Species lists

Foraminifera species list

The classification follows that of Loeblich and Tappan (1974) although it is intended that the following list will be updated in accord with Loeblich and Tappan (1988). Codes that are listed for each species represent the environment group assigned in this study and are as follows; M = marsh, B = Brackish, BM = Brackish/Marine, Mis = Marine (inner shelf) and Mp = Marine (planktonic).

Phylum **Protozoa**
Subphylum **Sarcodina**
Class **Rhizopodea**
Order **Foraminiferida**

BENTHIC SPECIES

Suborder **Textulariina** Delage and Herouard	
Superfamily **Lituolacea**	
Family **Rzehakinidae** Cushman	
Miliammina fusca (Brady)	M
Family **Trochamminidae** Schwager	
Subfamily **Trochammininae** Schwager	
Jadammina macrescens (Brady)	M
Trochammina inflata (Montagu)	M
Trochammina ochracea (Williamson)	Mis
Family **Textulariidae** Ehrenberg	
Spiroplectammina wrightii (Silvestri)	M
Suborder **Miliolina**	
Superfamily **Miliolacea**	
Family **Fischerinidae** Millet	
Subfamily **Cyclogyrinae** Loeblich and Tappan	
Cyclogyra involvens (Reuss)	Mis
Family **Nubeculariidae**	
Cornuloculina balkwilli (Macfadyen)	Mis
Family **Miliolidae** Ehrenberg	
Miliolinella subrotunda (Montagu)	Mis
Pyrgo species	Mis
Quinqueloculina species	Mis
Quinqueloculina cliarensis (Heron-Allen & Earland)	Mis
Quinqueloculina dimidiata Terquem	Mis
Quinqueloculina lata Terquem	Mis
Quinqueloculina oblonga (Montagu)	Mis
Quinqueloculina seminulum (Linné)	Mis
Suborder **Rotaliina**	
Superfamily **Nodosariacea**	
Family **Nodosariidae** Ehrenberg	
Lagena clavata (d'Orbigny)	Mis
Lagena doveyensis Haynes	Mis
Lagena laevis (Montagu)	Mis
Lagena semistriata Williamson	Mis
Lagena striata (d'Orbigny)	Mis
Lagena substriata Williamson	Mis

Lagena sulcata (Walker and Jacob)	Mis
Family **Polymorphinidae** d'Orbigny	
Fissurina species	Mis
Fissurina lucida (Williamson)	Mis
Fissurina marginata (Montagu)	Mis
Laryngosigma lactea (Walker and Jacob)	Mis
Oolina species	Mis
Oolina lineata (Williamson)	Mis
Oolina williamsoni (Alcock)	Mis
Superfamily **Buliminacea**	
Family **Turrilinidae** Cushman	
Buliminella elegantissima (d'Orbigny)	Mis
Family **Bolivinitidae** Cushman	
Bolivina pseudoplicata Heron-Allen and Earland	Mis
Brizalina species	Mis
Brizilina pseudopunctata (Höglund)	Mis
Brizilina variabilis (Williamson)	Mis
Family **Buliminidae**	
Bulimina species	Mis
Bulimina elongata d'Orbigny	Mis
Bulimina marginata d'Orbigny	Mis
Superfamily **Discorbacea**	
Family **Discorbidae** Ehrenberg	
Buccella frigida (Cushman)	BM
Gavelinopsis praegeri (Heron-Allen and Earland)	Mis
Rosalina species	Mis
Rosalina anomala Terquem	Mis
Rosalina williamsoni (Chapman and Parr)	Mis
Family **Asterigerinidae** d'Orbigny	
Asterigerinata mamilla (Williamson)	Mis
Superfamily **Spirillinacea**	
Family **Spirillinidae** Reuss	
Spirillina species	Mis
Spirillina vivipara Ehrenberg	Mis
Patellina corrugata Williamson	Mis
Superfamily **Rotaliacea**	
Family **Rotaliidae** Ehrenberg	
Subfamily **Rotaliinae** Ehrenberg	
Ammonia beccarii (Linné)	
v. *aberdoveyensis* Haynes	B
v. *batavus* (Hofker)	Mis
v. *limnetes* (Todd and Bronniman)	B
v. *tepida* (Cushman)	B
Family **Elphidiidae** Galloway	
Subfamily **Elphidiinae** Galloway	
Elphidium species	BM
Elphidium crispum (Linné)	BM
Elphidium cuvillieri Levy	Mis
Elphidium earlandi Cushman	Mis
Elphidium excavatum (Terquem)	BM
f. *clavatum* Cushman	BM
f. *lidoensis*	
f. *magna*	
Elphidium gerthi Van Voorthuysen	Mis
Elphidium incertum (Williamson)	Mis

Elphidium macellum (Fichtell and Moll)	BM
subsp. *spinosum* Atkinson	BM
Elphidium magellanicum Heron-Allen and Earland	BM
Elphidium margaritaceum (Cushman)	Mis
Elphidium oceanensis (d'Orbigny)	BM
Elphidium williamsoni Haynes	B
Haynesina species	BM
Haynesina depressulus (Walker and Jacob)	Mis
Haynesina germanica (Ehrenberg)	BM
Haynesina orbicularis (Brady)	Mis?
Family **Anomalinidae** Cushman	
Anomalina globulosa Chapman and Parr	Mis?
Superfamily **Orbitoidacea**	
Family **Cibicididae** Cushman	
Cibicides lobatulus (Walker and Jacob)	Mis
Family **Planorbulinidae** Schwager	
Planorbulina species	Mis
Planorbulina distoma Terquem	Mis
Superfamily **Cassidulinacea**	
Family **Caucasinidae**	
Fursenkoina fusiformis (Williamson)	Mis
Nonionella turgida (Williamson)	Mis

PLANKTONIC SPECIES

Superfamily **Globigerinacea**	
Globigerina bulloides d'Orbigny	Mp

Ostracod species list

The classification for marine and brackish species follows that of Athersuch, Whittaker and Horne (1989) and for freshwater species follows that of Griffiths and Evans (1995). Codes that are listed for each species represent the environment group assigned in this study and are as follows; F = Freshwater, Fls = Freshwater (low salinity), B = Brackish, BM = Brackish/Marine, M = Marine.

Phylum or sub-phylum **Crustacea** Pennant
Class **Ostracoda** Latreille
Subclass **Podocopa** G. W. Müller
Order **Podocopida** Sars
Suborder **Podocopina** Sars

MARINE AND BRACKISH SPECIES

Superfamily **Cypridacea** Baird	
Family **Pontocyprididae** G. W. Müller	
Propontocypris pirifera (G. W. Müller)	BM
Superfamily **Cytheracea** Baird	
Family **Cytheridae** Baird	
Cythere lutea O. F. Müller	M
Family **Eucytheridae** Puri	
Eucythere Brady species	M
Eucythere declivis (Norman)	M
Eucythere anglica Brady	M
Family **Leptocytheridae** Hanai	
Leptocythere Sars species	M
Leptocythere pellucida (Baird)	M
Leptocythere baltica Klie	BM
Leptocythere castanea (Sars)	B
Leptocythere lacertosa (Hirschmann)	B
Leptocythere macallana (Brady & Robertson)	M
Leptocythere porcellanea (Brady)	B
Leptocythere tenera (Brady)	M
Callistocythere littoralis (G. W. Müller)	M
Family **Cytherideidae** Sars	
Cyprideis torosa (Jones)	B
Sarsicytheridea bradii (Norman)	M
Sarsicytheridea punctillata (Brady)	M
Family **Cushmanideidae** Puri	
Pontocythere elongata (Brady)	BM
Family **Trachyleberididae** Sylvester-Bradley	
Acanthocythereis dunelmensis (Norman)	M
Carinocythereis Ruggieri species	M
Celtia quadridentata (Baird)	M
Pterygocythereis Blake species	M
Pterygocythereis jonesii (Baird)	M
Robertsonites tuberculatus (Sars)	M
Family **Hemicytheridae** Puri	
Hemicythere villosa (Sars)	BM
Aurila convexa (Baird)	M
Elofsonella concinna (Jones)	M
Heterocythereis albomaculata (Baird)	M
Finnmarchinella finmarchia (Sars)	M
Finnmarchinella barentzoevensis (Sars)	M

Family **Loxoconchidae** Sars	
Loxoconcha rhomboidea (Fischer)	BM
Loxoconcha elliptica Brady	B
Bonnyannella robertsoni (Brady)	M
Elofsonia baltica (Hirschmann)	B
Hirschmannia viridis (O. F. Müller)	BM
Palmoconcha guttata (Norman)	M
Palmoconcha laevata (Norman)	M
Nannocythere pavo (Malcomson)	M
Family **Paracytherideidae** Puri	
Paracytheridea cuneiformis (Brady)	M
Family **Cytheruridae** G. W. Müller	
Subfamily **Cytherurinae** G. W. Müller	
Cytherura gibba (O. F. Müller)	B
Hemicytherura cellulosa (Norman)	M
Hemicytherura clathrata	M
Semicytherura nigrescens (Baird)	BM
Semicytherura acuticostata (Sars)	M
Semicytherura angulata (Brady)	BM
Semicytherura cornuta (Brady)	M
Semicytherura sella (Sars)	BM
Semicytherura striata (Sars)	BM
Semicytherura tela Horne and Whittaker	BM
Subfamily **Cytheropterinae** Hanai	
Cytheropteron nodosum Brady	M
Cytheropteron pyramidale Brady	M
Family **Bythocytheridae** Sars	
Pseudocythere caudata Sars	M
Sclerochilus contortus (Norman)	M
Family **Paradoxostomatidae** Brady and Norman	
Paradoxostoma Fischer species	M
Paradoxostoma ensiforme Brady	M
Paradoxostoma normani Brady	BM
Paradoxostoma robinhoodi Horne & Whittaker	M
Paradoxostoma tenuissimum (Norman)	M
Paradoxostoma variabile (Baird)	BM
Cytherois fischeri (Sars)	B

FRESHWATER SPECIES

Superfamily **Darwinuloidea** Brady and Norman	
Family **Darwinulidae** Brady and Norman	
Darwinula stevensoni (Brady and Norman)	F(lst)
Superfamily **Cytheroidea** Baird	
Family **Limnocytheridae** Klie	
Subfamily **Limnocytherinae** Klie	
Limnocythere inopinata (Baird)	F(lst)
Superfamily **Cypridoidea** Baird	
Family **Candonidae** Kaufmann	
Subfamily **Candoninae** Kaufmann	
Candona angulata G. W. Müller	F(lst)
Candona candida (O. F. Müller)	F(lst)
Subfamily **Cyclocypridinae** Kaufmann	
Cyclocypris laevis (O. F. Müller)	F(lst)
Cypria ophtalmica (Jurine)	F(lst)

Family **Ilyocyprididae** Kaufmann	
Ilyocypris gibba (Ramdohr)	F(lst)
Family **Cyprididae** Baird	
Subfamily **Herpetocypridinae** Kaufmann	
Herpetocypris chevreuxi Sars	F(lst)
Subfamily **Cyprinotinae** Bronshtein	
Heterocypris salina (Brady)	F(lst)
Subfamily **Cypridopsinae** Kaufmann	
Cypridopsis vidua (O. F. Müller)	F
Sarscypridopsis aculeata (Costa)	F(lst)
Potamocypris zschokkei (Kaufmann)	F
Potamocypris villosa (Jurine)	F(lst)

Mollusc species list

The convention of the freshwater species follows that outlined by Kerney (1976). Provisional taxonomic lists for the marine molluscs is after Seaward (1990). Codes that are listed for each species represent the environment group assigned in this study and are as follows; F = Freshwater, B = Brackish and M = Marine.

Phylum or sub-phylum **Mollusca**
Class **Gastropoda** Cuvier
Subclass **Prosobranchia** Milne-Edwards

Order **Caenogastropoda** Cox
Superfamily **Valvatacea** Thompson
Family **Valvatidae** Thompson

Valvata cristata Müller	F

Superfamily **Littorinacea** Gray
Family **Littorinidae** Gray

Littorina littorea (Linné)	M

Superfamily **Rissoacea** Gray
Family **Hydrobiidae** Stimpson

Hydrobia ulvae (Pennant)	B

Order **Basommatophora**
Subclass **Pulmonata**
Family **Lymnaeidae**

Lymnaea palustris (Müller)	F
Lymnaea peregra (Müller)	F

Family **Ancylidae**

Acroloxus lacustris (Linné)	F

Fanily **Planorbidae**

Anisus vortex (Linné)	F
Gyraulus laevis (Alder)	F
Armiger crista (Linné)	F
Hippeutis complanatus (Linné)	F

Class **Bivalvia** Linné
Order **Eulamellibranchia** Perrier
Suborder **Schizodonta** Sterimann
Superfamily **Sphaeriacea** Thiele
Family **Sphaeriidae** Jeffreys

Sphaerium corneum (Linné)	F

Family **Pisidiidae** C. Pfeiffer

Pisidium personatum Malm	F
Pisidium obtusale (Lamarck)	F
Pisidium milium Held	F
Pisidium subtrucatum Malm	F
Pisidium nitidum Jenyns	F

Subclass **Teleodesmacea**
Order **Pseudolamellibranchia**
Superfamily **Cardiacea**
Family **Cardiidae**

Cersastoderma edule (Linné)	B

Diatom species list

The classification follows Hartley (1986). Codes that are listed for each species represent the salinity groups according to Hustedt (1953) and are as follows; F = Freshwater, B = Brackish, MB = Marine/Brackish, M = Marine.

Abbreviations of Ecological Groups (from Vos & de Wolf, 1988) :

(p)	plankton	(b)	benthic (from de Wolf, 1992)
(t)	tychoplankton		
(ep)	epipelon		
(e)	epiphytes		
(es)	episammon		
(a)	aerophilous		

EU Ecology unknown

Abbreviations of author's names :

Ag.	C. A. Agardh	Jørg.	E. Jørgensen
J. W. Bail	J. W. Bailey	Kütz.	F. T. Kützing
Bréb.	A de Brébisson	Lyngb.	H. C. L. Lyngbye
Brockm.	C. Brockmann	O. Müll.	O. Müller
Cleve	P.T. Cleve	Patr.	Patrick
Donk.	A. S. Donkin	H.et M. Perag.	H. et M. Peragallo
Ehrenb.	C. G. Ehrenberg	Pfitz.	E. Pfitzer
Greg.	W. Gregory	Pritch.	A. Pritchard
Grev.	R. K. Greville	Quek.	Quekett
Grun.	A. Grunow	Rabenh.	L. Rabenhorst
Hass.	A. H. Hassall	W. Sm.	W. Smith
Heib.	P. A. C. Heiberg	Turp.	P. Turpin
Hust.	F. Hustedt		

Order : **CENTRALES**		
Suborder : **Coscinodiscineae**	**Vos & de Wolf (1988) Denys (1992)**	**deWolf(1992)**
Family : **Thalassiosiraceae** Lebour, emend Hasle		
Cyclotella (Kütz.) Bréb.		
C. comta (Ehrenb.) Kütz.	F(p)	
C. sp.	EU	
Porosira Jørg.		
P. glacialis (Grun.) Jørg.	M(ep)	
Thalassiosira Cleve		
T. decipiens (Grun.) Jørg.	M(p)	
Family : **Melosiraceae** Kütz.		
Paralia Heib.		
P. sulcata (Ehrenb.) Cleve	M(p)	
Pdosira Ehrenb.		
P. stelligera (J. W. Bail.) A. Mann	M(p)	
Rhaphoneis Ehrenb.		
R.. amphiceros (Ehrenb.) Ehrenb.	M(t)	
R. minutissima Hust.	M(t)	
R. surirella (Ehrenb.) Grun. in Van Heurck	M(t)	
[*R. nitida* (Greg.) Grun.]		

Family : **Coscinodiscaceae** Kütz.		
Coscinodiscus Ehrenb.		
C. apiculatus Ehrenb.		
var. *ambiguus* Grun.	M(p)	
C. eccentricus Ehrenb.	M(p)	
[*C. divisus* Grun.]		
C. radiatus Ehrenb.	B(p)	
C. sp.	B(p)	
Family : **Hemisdicaceae** Hendey, emend Simonsen		
Actynocyclus Ehrenb.		
A. roperii (Bréb.) Grun. in Van Heurck	M(p)	
A. senarius (Ehrenb.) Ehrenb.	M(p)	
A. undulatus J. W. Baill.	M(p)	
[*A. senarius* (Ehrenb.) Ehrenb.]		
A. normanii (Greg. ex. Greg.) Hust. ex Van Land.	B(p)	
Suborder :**Biddulphiinae**		
Family : **Biddulphiaceae** Kütz.		
Subfamily : **Biddulphioides** Schütt		
Biddulphia Gray		
B. aurita (Lyngb.) Bréb.	EU	M(e)
[*B. alternans* (J. W. Bail.) Van Heurck]		
Eutonogramma Weisse		
E. dubium Hust.	MB(ep)	
Subfamily :**Hemiauloideae** Jouse, Kiselev et Poret.		
Cymatosira Grun.		
C. belgica Grun. in Van Heurck	M(t/p)	
Order : **PENNALES**		
Suborder : **Araphidinae**		
Family : **Diatomaceae** Dumortier		
Diatoma Bory (nom. cons.)		
D. sp.	EU	
Fragilara Lyngbd.		
F. brevistriata Grun. in Van heurck	BF(t)	
F. construens (Ehrenb.) Grun.	BF(t)	
var. *subsalina* Hust.	BF(t)	
var. *venter* (Ehrenb.) Grun. in Van heurck	BF(t)	
F. dilatata (Bréb.) Lange-Bertalot	BF(t)	
[*Synedra capitata* Ehrenb.]		
F. famelica var. *famelica* Lange-Bertalot	BF(t)	
[*Synedra famelica* Kütz.]		
F. lapponica Grun.in Van heurck	BF(t)	
F. pinnata Ehrenb.	BF(t)	
F. virescens Ralfs	BF(t)	
var. *exigua* Grun. in Van heurck	BF(t)	
Grammatophora Ehrenb.		
G. angulosa Ehrenb.	MB(e)	
G. sp.	EU	
Meridion Ag.		
M. circulare (Grev.) Ag.	F(p)	
var. *constrictum* (Ralfs) Van Heurck	F(p)	

Opephora Petit		
O. gemmata (Grun.) Hust.	MB(es)	
O. pacifica (Grun.) Petit	MB(es)	
O. sp.	EU	
Plagiogramma Grev.		
P. brockmanii Hust.	EU	M(e)
P. leve (Greg.) Ralfs	MB(es)	
P. van-heurckii Grun. in Van Heurck	M(t)	
P. sp.	EU	
Synedra Ehrenb.		
S. crystallina (Ag) Kütz.	M(e)	
S. fasciculata (Ag) Kütz., excl. descr.	MB(e)	
S. pulchella Ralfs ex Kütz.	MB(e)	
S. sp.	EU	
Tabellaria Ehrenb. ex Kütz.		
T. flocculosa(Roth) Kütz.	BF(t)	
Thalassionema Grun.		
T. nitszchioides Grun.	M(p)	

Suborder : **Raphidinae**

Family : **Eunotiaceae** Kütz.		
Eunotia Ehrenb.		
E. formica (Ehrenb.)	F(e)	
[*E. flexuosa* Kütz.]		
E. minor (Kütz.) Grun. in Van heurck	F(e)	
[*E. pectinalis* var. *minor* (Kütz.) Rabenh.]		
E. paludosa Grun.	F(e)	
E. praerupta Ehrenb.	F(e)	
E. veneris sensu Van Heurck et auct. non (Kütz.) De Toni	F(e)	
[*E. vanheurckii* Patr.]		
Family : **Achnanthaceae** Kütz.		
Achnanthes Bory		
A. biasolettiana Grun. in Cleve et Grun.	EU	
[var. *ventricosa* Krasse]		
A. clevei Grun. in Cleve et Grun.	F(e)	
A. conspicua A. Mayer	F(e)	
A. delicatula (Kütz.) Grun. in Cleve et Grun.	MB(es)	
A. hauckiana Grun. in Cleve et Grun.	EU	B(e)
[A. *hallandica* A. Cleve-Euler]		
A. lanceolata (Bréb. ex. Kütz.) Grun. in Cleve et Grun.	F(e)	
var. *dubia* Grun. in Cleve et Grun.	F(e)	
[*var. bimaculata* Hust.]		
A. minutissima Kütz.	F(e)	
A. pseudogroenlandica Hendey	EU	
A. rosii Hust.	EU	
A. thermalis (Rabenh.) Schoenfeld	EU	
A. sp.	EU	
Cocconeis Ehrenb.		
C. pediculus Ehrenb.	BF(e)	
C. placentula Ehrenb.	BF(e)	
var. *lineata* (Ehrenb.) Van Heurck	BF(e)	
var. *stauroneiformis* W. Sm	MB(e)	
[*C. stauroneiformis* (W. Sm.) Okuno]		

Family : **Naviculaceae** Kütz.	
Amphiprora Kütz., non *Amphiprora* Ehrenb.	
A. sp.	EU
Amphora Ehrenb. ex Kütz.	
A. acutiuscula Kütz.	MB(ep)
[*A. acuta* Greg.]	
A. arcus Greg.	EU
A. baccilaris Greg.	MB(ep)
A. coffaeiformis (Ag.) Kütz.	MB(ep)
A. commutata Grun. in Van Heurck	M(ep)
A. dibia Greg.	MB(ep)
A. ovalis (Kütz.) Kütz.	F(ep)
A.. ovalis var. *lybica* Ehrenb. ex Kütz.	F(ep)
[*A. ovalis* var. *affinis* (Kütz.) Van Heurck]	
A. salina W. Sm.	MB(ep)
[*A. coffaeiformis* (Ag.) Kütz.]	
A. sp.	EU
Anomoeoneis Pfitz.	
A. vitrea (Grun.) R. Ross in Patr. et Reimer	EU
[*A. sphaerophora* (Ehrenb.) Pfitz.]	
A. sp.	EU
Caloneis Cleve	
C. amphisbaeana (Bory) Cleve	MB(ep)
C. westii (W. Sm.) Hendey	MB(ep)
C. sp.	EU
Cymbella Ag.	
C. affinis Kütz.	F(e)
C. delicatula Kütz.	F(e)
C. helvetica Kütz.	F(e)
C. silesiaca Bleich ex Rabenh.	F(e)
[*C. minuta* Hilse ex Rabenh.	
var. *silesiaca* (Bleich ex Rabenh.) Reimer in Patr. et Reimer]	
C. sp.	EU
Diploneis Ehrenb. ex Cleve	
D. aestuari Hust.	MB(ep)
D. didyma (Ehrenb.) Cleve	MB(ep)
D. ovalis (Hilse) Cleve	MB(a)
D. smithii (Bréb. ex W. Sm) Cleve	M(ep)
D. sp.	EU
Frustulia Rabenh. (non. cons.)	
F. rhomboides var. *viridula* (Bréb. ex Kütz.) Cleve	F(ep)
Gomphonema Ehrenb.	
[*abbreviatum* Ag.]	
G. angustatum (Kütz.) Rabenh.	F(e)
G. angustum Ag.	F(e)
Gyrosigma Hass. (nom. cons.)	
G. hippocampus (Ehrenb.) Hass.	MB(ep)
G. macrum (W. Sm.) Griffith et Henfrey	MB(ep)
G. spenceri (Queck.) Griffith et Henfrey	MB(ep)
Navicula Bory	
N. abrupta (Greg.) Donk.	MB(ep)
N. amphibola Cleve	F(ep)
[*N. americana* Ehrenb.]	
N. cincta (Ehrenb.) Ralfs in Pritch.	MB(ep)
[*N. cari* Ehrenb. var. *cincta* (Ehrenb.) Cleve]	
N. clementis Grun.	F(ep)
N. contenta Grun. in Van Heurck	MB(ep)
N. crucifera Grun ex A. Schmidt	MB(ep)
[*N. cruciculoides* Brockm.]	

N. crucigera (W. Sm.) Cleve	MB(ep)	
[*N. cruciculoides* Brockm.]		
N. cryptotenella Lange-Bertalot	MB(ep)	
N. digito-radiata (Greg.) Ralfs in Pritch.	MB(ep)	
N. eidrigeana J.R. Carter	F(ep)	
N. flanatica Grun.	MB(ep)	
*N. flanatica sp.*2	MB(ep)	
N. forcipata Grev.	MB(ep)	
N. halophila (Grun. ex Van Heurck) Cleve	MB(ep)	
N. humerosa Bréb. ex W. Sm.	M(ep)	
N. mutica Kütz.	BF(a)	
var. *conhii* (Hilse) Grun. in Van Heurck	BF(a)	
N. palpepabris Bréb. ex W. Sm.	MB(ep)	
N. pelliculosa (Kütz.) Hilse in Rabenh.	F(ep)	
N. peregrina (Ehrenb.) Kütz.	M(ep)	
N. phyllepta Kütz.	MB(ep)	
N. pusilla W. Sm.	MB(ep)	
N. pygmea Kütz.	MB(ep)	
N. ramosissima (Ag.) Cleve	EU	
N. rhyncocephala Kütz.	MB(ep)	
N. salinarum Grun. in Cleve et Grun.	MB(ep)	
N. subforcipata Hust.	MB(ep)	
N. sp.	EU	
N. sp. 1	EU	
Pinnularia Ehrenb. (nom. cons.)	MB(es)	
P. ambigua Cleve	MB(ep)	
P. lagerstedtii (Cleve) A. Cleve-Euler	F(ep)	
P. lata (Bréb.) *Rabenh.*	EU	
P. stomatophora (Grun. ex A. Schmidt) Cleve	F(ep)	
P. subcapitata Greg.	F(ep)	
P. viridis (Nitszch) Ehrenb.	BF(a)	
P. sp.	EU	
Pleurosigma W. Sm. (nom. cons.)		
P. angulatum (Queckett) W. Sm.	MB(ep)	
P. salinarum (Grun.) Grun. in Cleve et Grun.	MB(ep)	
Rhoiscophenia Grun.		
R. marina M. Schmidt in A. Schmidt	MB(ep)	
Stauroneis Ehrenb.		
S. amphioxys Greg. var. *obtusa* Hendey	MB(ep)	
S. phoenicentron (Nitzsch) Ehrenb.	MB(a)	
Trachyneis Cleve		
T. aspera (Ehrenb.) Cleve	M(ep)	
Family : **Auriculaceae** Hendey		
Auricula Castr. (nom. cons.)		
A. dubia H. et M Perag.	EU	B(b)
[*A. decipiens* Grun. in Van Heurck) Cleve]		
Family : **Epithemiaceae** Grun.		
Epithemia Bréb. ex Kütz.		
E. adnata (Kütz.) Rabenh.	F(e)	
E. sp.	EU	
Rhopalodia O. Müll. (nom. cons.)		
R. brebissonii Krammer	MB(e)	
[*R. musculus* var. *succinta* sensu H. et M. Perag.]		
R. gibberula (Erenhb.) O. Müll.	MB(e)	
R. sp.	EU	

Family : **Nitszchiaceae** Grun.	
Denticula Kütz.	
D. subtilis Grun.	MB(es)
Hantszchia Grun. (nom. cons.)	
H. amphioxys (Ehrenb.) Grun.	BF(a)
Nitszchia Hass. (nom. cons.)	
N. acuminata (W. Sm.) Grun.	MB(ep)
N. amphibia Grun.	F(e)
N. debilis Grun. in Cleve et Grun. nom. superfl.	MB(ep)
[*N. cylindrus* (Grun. ex Cleve) Hasle]	
N. filiformis (W. Sm.) Van Heurck	MB(ep)
N. fonticola Grun. in Van Heurck	F(e)
N. hungarica Grun.	M(ep)
N. navicularis (Bréb. ex Kütz.) Grun. in Cleve et Grun.	M(ep)
N. panduriformis Greg.	
N. *punctata* (W. Sm.) Grun.	MB(ep)
var. *constricta* (Grun.) Van Heurck	MB(ep)
N. stigmaformis	EU
N. tryblionella Hantzsch in Rabenh.	MB(ep)
N. sp.	EU
Family : **Surirellaceae** Kütz.	
Surirella Turp.	
S. amoricana H. et M. Perag.	M(ep)
S. ovalis Bréb.	MB(ep)
S. ovata Kütz.	MB(ep)
S. patella Kütz.	EU

Appendix C

Presented here are SEM photographs of all the main species of Foraminifera (Plates 1 and 2) and Ostracoda (Plates 3 to 7) identified in this study. Details of each photographed specimen are also provided as follows: species name, dimensions (millimetres), view (where appropriate) location in Cree estuary region and approximate age of specimen. The location codes are all borehole locations (see Appendices D and E) with the exceptions of BB/F and BB which are the Brighouse Bay foreshore pink clays and the modern sandy beach respectively. The approximate ages of the specimens are coded as LD (Late Devensian), F (Flandrian) and M (Modern).

The dimension provided for each foraminifera test is either width by height or just the test diameter. If the specimen is trochospiral then the dorsal or ventral view is indicated.

The details for each ostracod valve include left (LV) or right (RV) valve, growth stage (i.e. adult = A, juvenile instar = A-number), sex if known (i.e. male = m, female = f) and internal or external lateral view (int. or ext. lat.). The dimensions are length by height.

Plate 1

Figure 1 *Miliammina fusca* (Brady) 0.33 x 0.67mm, PAL/6, F.

Figure 2 *Trochammina inflata* (Montagu) 0.48mm, dorsal view, PAL/6, F.

Figure 3 *T. inflata* (Montagu) 0.34mm, dorsal view, PAL/6, F.

Figure 4 *Jadammina macrescens* (Brady) 0.34mm, dorsal view, PAL/6, F.

Figure 5 *Cyclogyra involvens* (Reuss) 0.18mm, side view, CWF/A, F.

Figure 6 *Cornuloculina balkwilli* (Macfadyen) 0.15mm, side view, CWF/A, F.

Figure 7 *Ammonia beccarii* (Linné) var. *batavus* Hofker 0.4mm, dorsal view, BB/42, F.

Figure 8 *A. beccarii* (Linné) var. *batavus* Hofker 0.42mm, ventral view, BB/42, F.

Figure 9 *A. beccarii* (Linné) var. *tepida* Cushman/*aberdoveyensis* Haynes 0.3mm, dorsal view, BB/42, F.

Figure 10 *A. beccarii* (Linné) var. *tepida* Cushman/*aberdoveyensis* Haynes 0.31mm, ventral view, BB/42, F.

Figure 11 *A. beccarii* (Linné) var. *limnetes* Todd and Brönnimann 0.29mm, dorsal view, CWF/A, F.

Figure 12 *A. beccarii* (Linné) var. *limnetes* Todd and Brönnimann 0.26mm, ventral view, CWF/A, F.

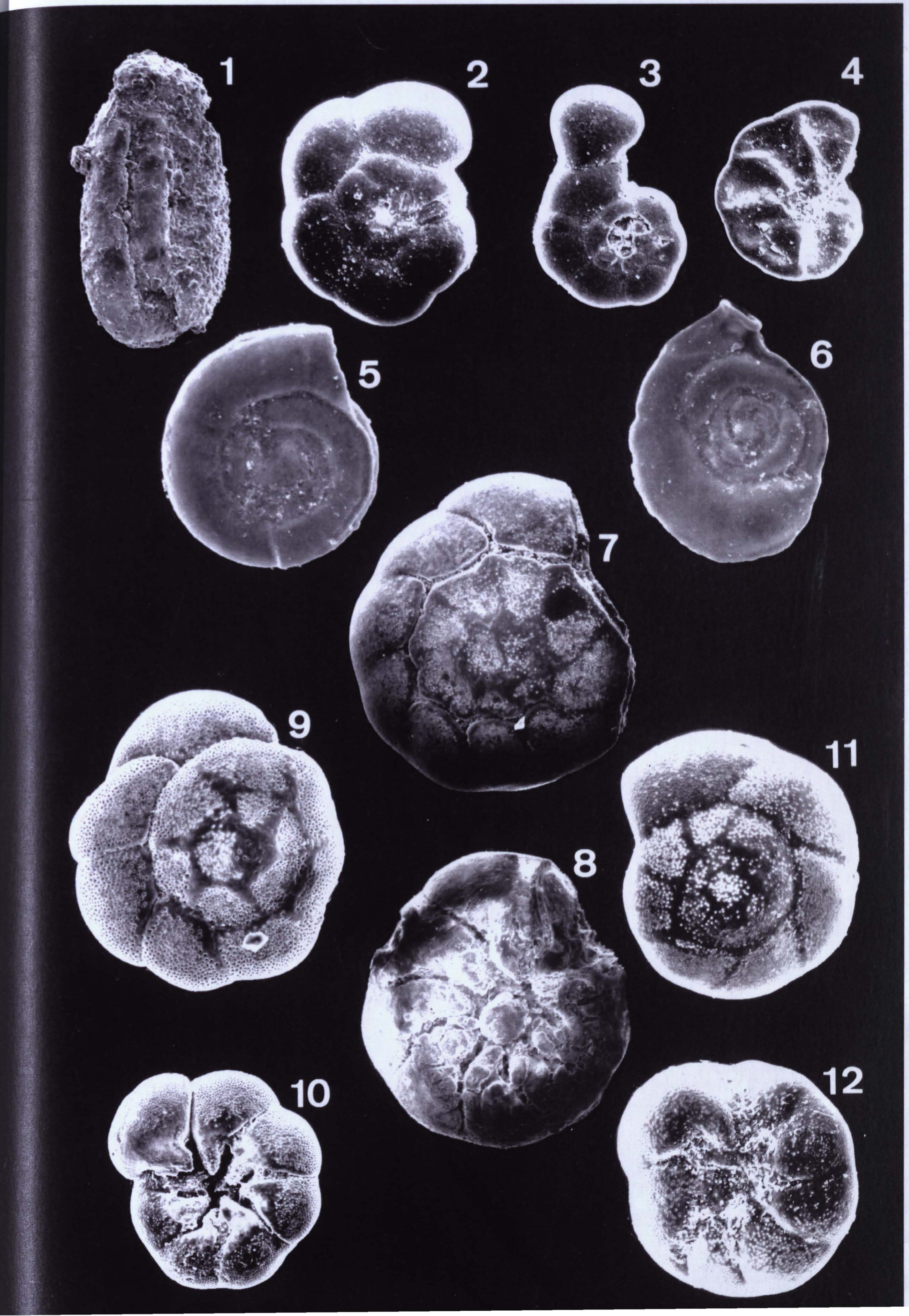


Plate 2

Figure 1 *Elphidium excavatum* forma *clavata* Cushman 0.46mm, side view, BB/F, LD.

Figure 2 *E. excavatum* type (Terquem) 0.95mm, side view, BB/F, LD.

Figure 3 *E. excavatum* forma *lidoensis* Cushman 0.2mm, side view, CWF/A, F.

Figure 4 *E. macellum* (Fichtel and Moll) *var. spinosum* (Atkinson) 0.52mm, side view, BB/42, F.

Figure 5 *E. macellum* (Fichtel and Moll) 0.43mm, side view, BB/42, F.

Figure 6 *E. macellum* (Fichtel and Moll) *var. spinosum* (Atkinson) 0.46mm, side view, BB/42, F.

Figure 7 *E. oceanensis* (d'Orbigny) 0.24mm, side view, CWF/A, F.

Figure 8 *E. williamsoni* Haynes 0.37mm, side view, CWF/A, F.

Figure 9 *E. williamsoni* Haynes 0.48mm, side view, BB/42, F.

Figure 10 *Haynesina orbicularis* (Brady) 0.65mm, side view, BB/F, LD.

Figure 11 *H. germanica* (Ehrenberg) 0.28mm, side view, CWF/A, F.

Figure 12 *Anomalina globulosa* type Chapman and Parr 0.28mm, dorsal view, CC/2, F.

Figure 13 *A. globulosa* type Chapman and Parr 0.32, ventral view, CC/2, F.

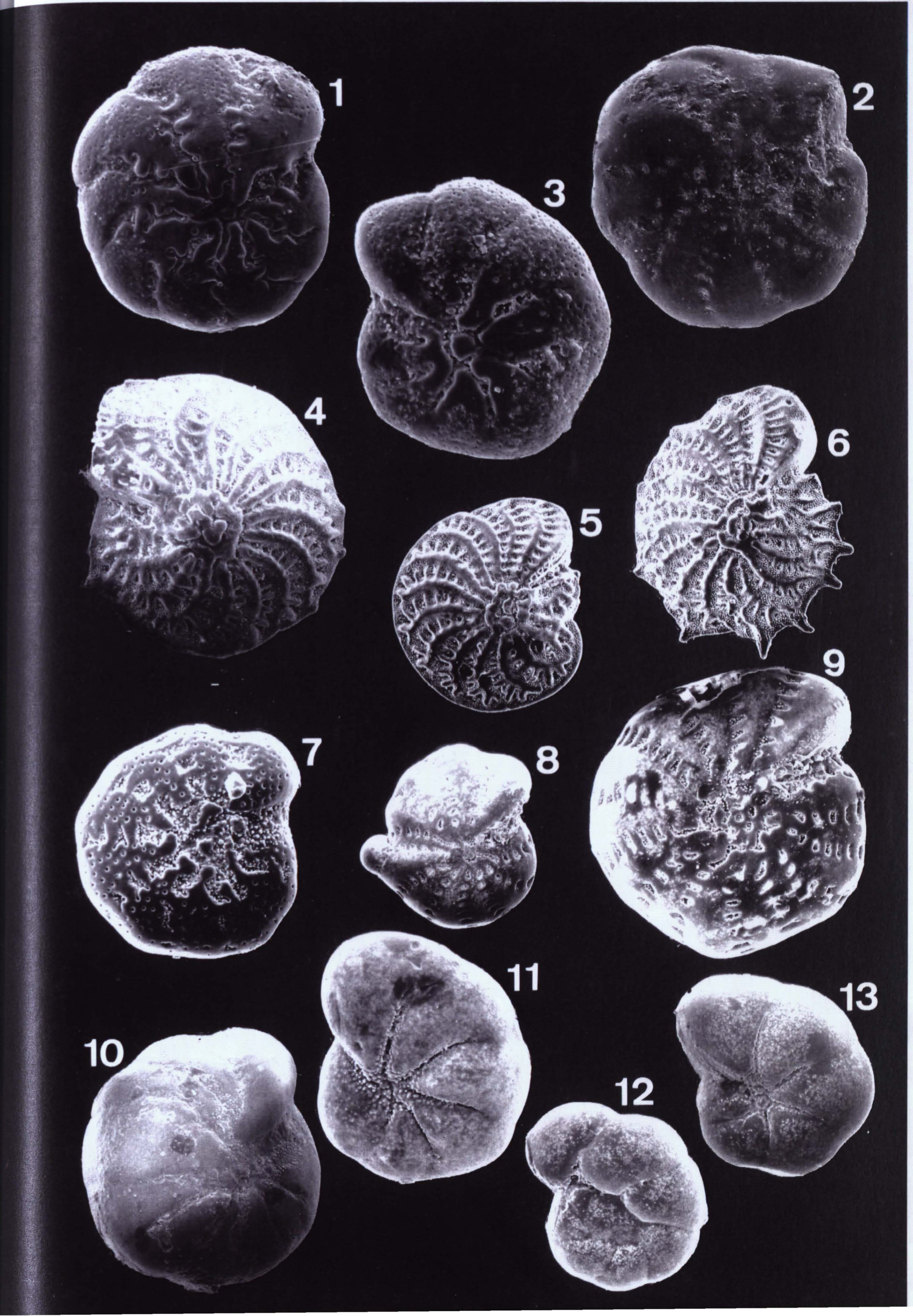


Plate 3

Figure 1-13 *Leptocythere castanea* (Sars) scale bar = 0.1mm, CWF/A, F.

Figure 1 RVA (ext. lat.)

Figure 2 LVA (ext. lat.)

Figure 3 RVA-1 (ext. lat.)

Figure 4 LVA-1 (ext. lat.)

Figure 5 LVA-2 (int. lat.)

Figure 6 LVA-2 (ext. lat.)

Figure 7 RVA-3 (ext. lat.)

Figure 8 RVA-4 (ext. lat.)

Figure 9 LVA-4 (ext. lat.)

Figure 10 RVA-5 (ext. lat.)

Figure 11 LVA-5 (ext. lat.)

Figure 12 RVA-6 (ext. lat.)

Figure 13 LVA-6 (ext. lat.)

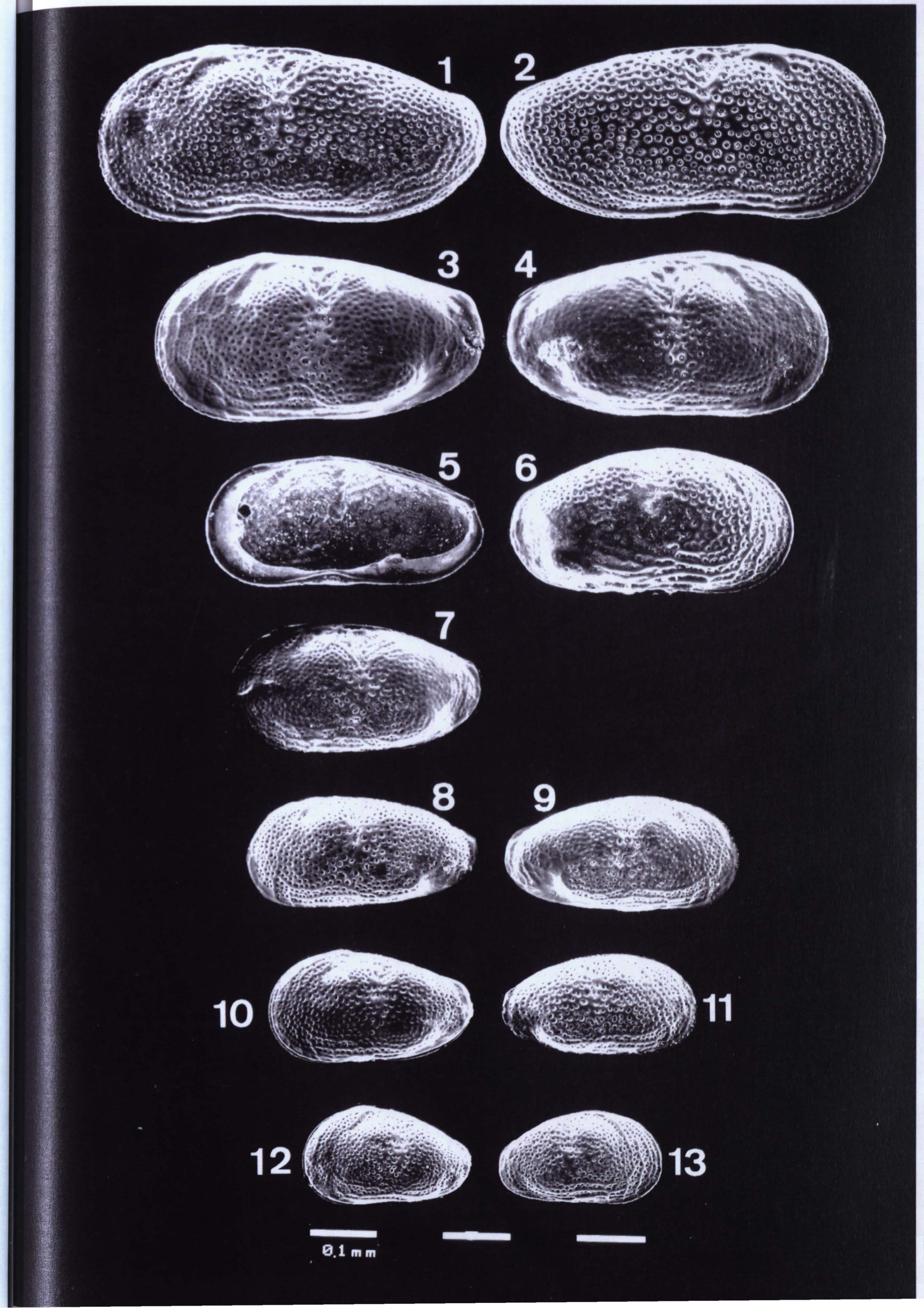


Plate 4

Figure 1 *Cythere lutea* O. F. Müller 0.74 x 0.43mm, RVA (ext. lat.), BB, M.

Figure 2 *Leptocythere pellucida* (Baird) 0.70 x 0.29mm, LVA (ext. lat.), BB/42, F.

Figure 3 *Leptocythere lacertosa* (Hirschmann) 0.42 x 0.19mm, LVA (ext. lat.), CWF/A, F.

Figure 4 *L. lacertosa* (Hirschmann) 0.42 x 0.18mm, RVA (int. lat.), CWF/A, F.

Figure 5 *Cyprideis torosa* (Jones) 1.1 x 0.6mm, LVA/m (ext. lat.), BB/42, F.

Figure 6 *C. torosa* (Jones) 1.0 x 0.7mm, LVA/f (ext. lat.), BB/42, F.

Figure 7 *Sarsicytheridea punctillata* (Brady) 0.78 x 0.39mm, LVA/m (ext. lat.), BB/F, LD.

Figure 8 *S. punctillata* (Brady) 0.68 x 0.40mm, LVA/f (ext. lat.), BB/F, LD.

Figure 9 *S. punctillata*? (Brady) 0.66 x 0.37mm, RV? (ext. lat.), BB/F, LD.

Figure 10 *Pontocythere elongata* (Brady) 0.59 x 0.27mm, RVA (ext. lat.), BB/42, F.

Plate 5

Figure 1 *Pterygocythereis jonesii* (Baird) 0.95 x 0.43mm, LVA (ext. lat.), BB/42, F.

Figure 2 *Robertsonites tuberculatus* (Sars) 0.68 x 0.38mm, LVJ (ext. lat.), BB/42, F.

Figure 3 *Hemicythere villosa* (Sars) 0.70 x 0.35mm, RVA/m (ext. lat.), BB/42, F.

Figure 4 *Elofsonella concinna* (Jones) 0.88 x 0.48mm, RV? (ext. lat.), BB/42, F.

Figure 5 *Aurila convexa* (Baird) 0.75 x 0.48mm, RVA (ext. lat.), BB/42, F.

Figure 6 *Finnmarchinella barentzovoensis* (Mandelstam) 0.52 x 0.23mm, LVA (ext. lat.), CWF/A, F.

Figure 7 *Loxoconcha rhomboidea* (Fischer) 0.63 x 0.43mm, LVA (ext. lat.), BB, M.

Figure 8 *L. elliptica* Brady 0.7 x 0.39mm, RVA/m (ext. lat.), BB/42, F.

Figure 9 *Hirschmania viridis* (O. F. Müller) 0.4 x 0.25mm, RV? (ext. lat.), CWF/A, F.

Figure 10 *Palmoconcha laevata* (Norman) 0.5 x 0.27mm, RVA (ext. lat.), BB, M.

Plate 6

Figure 1 *Palmoconcha guttata* (Norman) 0.56 x 0.35mm, LVA (ext. lat.), CWF/A, F.

Figure 2 *P. guttata* (Norman) 0.47 x 0.28mm, LVA (ext. lat.), CWF/A, F.

Figure 3 *Semicytherura nigrescens* (Baird) 0.34 x 0.18, RVA-? (ext. lat.), CWF/A, F.

Figure 4 *S. angulata* (Brady) 0.42 x 0.19mm, RVA (ext. lat.), CWF/A, F.

Figure 5 *Cytheropteron nodosum* Brady 0.59 x 0.29mm, RV? (ext. lat.), BB/42, F.

Figure 6 *Paradoxostoma normani* Brady 0.47 x 0.23mm, RV? (ext. lat.), CWF/A, F.

Figure 7 *Cytherois fischeri* (Sars) 0.42 x 0.16mm, RV? (ext. lat.), CWF/A, F.

Figure 8 *Limnocythere inopinata* (Baird) 0.65 x 0.32mm, RVA (ext. lat.), BB/42, F.

Figure 9 *Candona angulata* G. W. Müller x , RVA (ext. lat.), BB/42, F.

Figure 10 *Candona candida* (O. F. Müller) 1.05 x 0.6mm, LVA/f (ext. lat.), BB/42, F.

Figure 11 *C. candida* (O. F. Müller) 1.2 x 0.5mm, RVA/m (ext. lat.), BB/42, F.

Plate 7

Figure 1 *Pseudocandona rostrata* (Brady and Norman) 0.86 x 0.46mm, RVA (ext. lat.), BB/42, F.

Figure 2 *Cyclocypris laevis* (O. F. Müller) 0.49 x 0.32mm, RVA (ext. lat.), BB/42, F.

Figure 3 *Cypria ophtalmica* (Jurine) 0.59 x 0.40mm, LVA (ext. lat.), BB/42, F.

Figure 4 *Ilyocypris gibba* (Ramdohr) 0.53 x 0.31mm, RV? (ext. lat.), BB/42, F.

Figure 5 *Herpetocypris cf. chevreuxi* Sars 1.35 x 0.6mm, LVA (ext. lat.), BB/42, F.

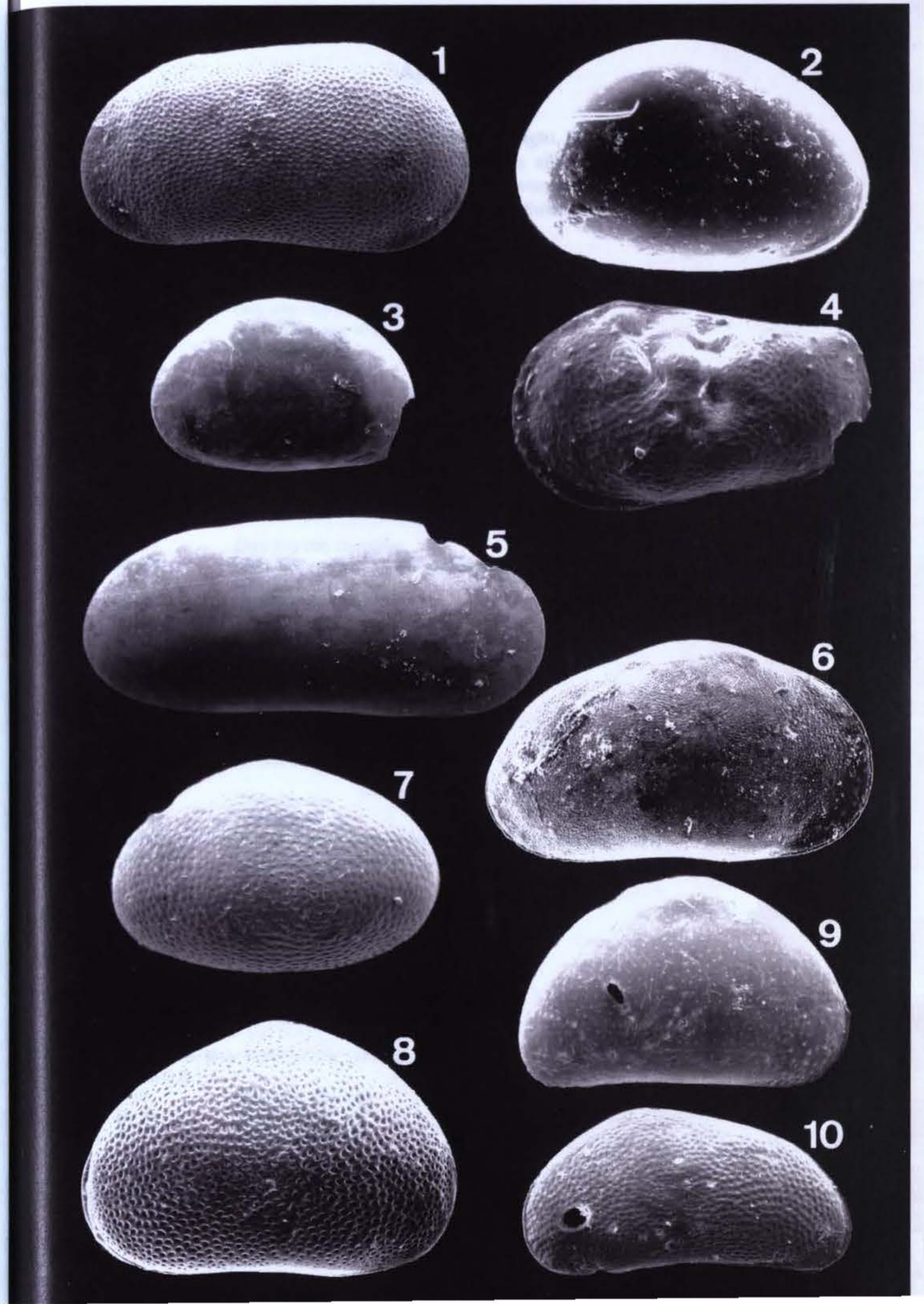
Figure 6 *Heterocypris salina* (Brady) 0.9 x 0.55mm, LVA (ext. lat.), BB/42, F.

Figure 7 *Cypridopsis vidua* (O. F. Müller) 0.73 x 0.47mm, LVA (ext. lat.), BB/42, F.

Figure 8 *Sarscypridopsis aculeata* (Costa) 0.63 x 0.43mm, LVA (ext. lat.), BB/42, F.

Figure 9 *Potamocypris villosa* (Jurine) 0.74 x 0.46mm, LV? (ext. lat.), BB/42, F.

Figure 10 *Potamocypris zschokkei* (Kaufmann) 0.73 x 0.36mm, RVA (ext. lat.), BB/42, F.



Appendix D

Borehole records for Brighouse Bay, Kirkcudbright, SW Scotland
Information provided for each borehole includes site code and borehole number, national grid reference (either 8 or 10 figure reference, height of borehole surface (m O.D.) and stratigraphical descriptions (depth in centimetres).

Transect C: Hole 1 (NX 263827 5465154)
9.63m O.D.

0-40	Grey silty clay (mottling)
40-54	Grey/brown organic silt
54-83	Peat (dark black)
83-117+	Blue grey gritty clay

Transect C: Hole 2 (NX 263809 546146)
9.59m O.D.

0-21	Grey silty clay (mottling)
21-43+	Blue grey gritty clay + clasts

Transect B: Hole 1 (NX 263856 546148)
9.54m O.D.

0-32	Grey silty clay (mottling)
32-60+	Light blue grey silty sand + angular clasts

Transect B: Hole 2 (NX 263837 546139)
9.30m O.D.

0-25	Silty grey clay
25-49	Grey/brown organic silt
49-74	Light grey clay (some OM)
74-95	Grey brown organic silt
95	Solid

Transect B: Hole 3 (NX 263819 546129)
9.12m O.D.

0-26	Grey silty clay
26-70	Grey organic silt
70-146	Peat (dark grey/brown) [carbonised wood fragment at 131-137]
146-185+	Light blue grey gritty clay

Transect B: Hole 4 (NX 263805 546120)
9.04m O.D.

0-31	Grey organic silt
31-55	Light grey clay
55-70	Grey organic silt
70-151	Peat (brown)
151-174+	Light blue gritty clay

Transect B: Hole 5 (NX 263785 546109)
9.11m O.D.

0-30	Dark grey silty sand
30-52	Brown organic silt
52-71	Light grey clay
71-112	Brown organic silt
112-136	Peat (dark brown)
136-169+	Light grey blue gritty clay

Transect B: Hole 6 (NX 263767 546099)
9.23m O.D.

0-20	Grey silty sand
20-29	Grey silty organic silt
29-33+	Blue organic gritty silt

Transect B: Hole 7 (NX)
9.26m O.D.

0-15	Top soil

Could not penetrate any further (at edge of rock structure)

Transect B: Hole 8 (NX)
9.21m O.D.

0-56	Grey silty clay (mottling)

Could not penetrate any further (vicinity of stream debris)

Transect A: Hole 1 (NX 263866 546131)
9.52m O.D.

0-60	Grey silty clay (mottling)
60-70	Grey medium/coarse sand
70-95	Grey clay (mottling)
95-134	Grey organic silt
134-150	Brown organic silt
150-173	Blue grey medium gravel to coarse angular sand
173-183	Brown organic silt
183-205	Blue grey medium/coarse sand
205-228	Peat (brown)
228-230+	Grey clay

Transect A: Hole 2 (NX 263849 546121)
9.36m O.D.

0-50	Grey silty clay (mottling)
50-90	Light grey clay [some wood fragments]
90-109	Darker grey organic silt
109-145	Peat (dark brown)
145-148	Blue grey coarse/medium sand
148-225	Peat (dark brown)
225-236	Blue gritty clay

Transect A: Hole 3 (NX 263830 546111)
9.23m O.D.

0-44	Grey silty clay (mottling)
44-69	Blue gery coarse/medium silty sand
76-150	Grey brown organic silt
150-187	Peat (black/grey) [burnt wood fragments (alder) at 168-175]
187-189+	Blue grey gritty clay

Transect A: Hole 4 (NX 263815 546101)
8.97m O.D.

0-27	Grey silty clay (mottling)
27-64	Light grey silty sand
64-76	Grey organic silt
76-78	Blue grey fine sand
78-234	Peat (brown) [wood fragments at 161-164 and 214-217]
234-268+	Blue grey gritty clay

Transect A: Hole 5 (NX 263796 546091)
9.04m O.D.

0-28	Grey silty sand
28-37	Dark grey organic silt
37-54	Light grey clay
54-86	Brown organic silt
86-214	Peat (brown)
214-261+	Light grey silty clay

Transect A: Hole 6 (NX 263778 546083)
9.15m O.D.

0-22	Grey silty sand
22-28	Grey shelly sand
28-47	Peat (brown)
47-84	Grey brown organic silt
84-237	Peat (brown)
237-248	Grey silt
248-258+	Blue grey gritty clay

Transect A: Hole 7 (NX 263757 546071)
9.01m O.D.

0-34	Grey silty sand
34-50	Grey organic silt
50-55	Wood
55-72	Grey clay
72-180	Peat (dark black)
180-183+	Blue grey gritty clay

Transect A: Hole 8 (NX 263736 546058)
8.84m O.D.

0-46	Brown sandy silt
46-60	Grey clay
60-70	Peat (black)
70-74	Grey clay
74-76	Wood
76-127	Peat (Dark brown/black)
127-129+	Blue grey gritty clay

Transect A: Hole 9 (NX 263718 546046)
8.83m O.D.

0-28	Grey brown sandy silt
28-46	Light grey clay
46-51	Wood
51-95	Peat (black) [Wood fragment at 69-74]
95-100+	Blue grey gritty clay

Transect 1: Hole 1 (NX 263679 546005)
9.58m O.D.

0-15	Top Soil
15-58	Silty sand
58-75	Peat (dark brown/black) well humified
75-84	Grey silty clay (Transitional)
84-100+	Blue grey clay (high fine sand content)

Transect 1: Hole 2 (NX 263696 546015)
9.15m O.D.

0-7	Top soil
7-26	Sandy organic silt
26-50	Peat (dark black)
50-70	Grey silty clay, some organic matter
70-90	Peat (black)
90-110	Grey silty clay + OM (Transitional)
110-129	Blue grey clay (sandy with clasts)
129-142+	Brown grey silty clay (no clasts)

Transect 1: Hole 3 (NX 263714 546025)
8.90m O.D.

0-7	Top soil
7-29	Sandy organic silt
29-57	Blue/grey sandy clay
57-72	Sandy organic silt
72-122	Peat (very dark)
122-127	Silty clay + OM (Transitional)
127-144	Blue grey clay (silt + sand)
144-197+	Brown grey clay

Transect 1: Hole 4 (NX 263732 546034)
8.71m O.D.

0-29	Top soil
29-69	Brown silty clay + OM
69-114	Peat (black + well humified + silt)
114-162	Peat (brown + poorly humified + sedge peat)
162-170	As above but increasing clay content with depth (Transitional)
170-196	Blue grey clay (angular clasts)
196-230	Grey brown clay (no clasts)

Transect 1: Hole 5 (NX 263748 546044)
8.66m O.D.

0-47	Top soil
47-62	Brown silty peat
62-80	Organic silt + wood (alder?)
80-105	Organic silt + sand
105-221	Brown peat (Poorly humified + sedge peat)
221+	Blue grey clay (sandy + angular clasts)

Transect 1: Hole 6 (NX 263770 546055)
8.37m O.D.

0-37	Top soil
37-48	Peat (Dark brown + humified)
48-213	Peat (light brown + poorly humified) [wood fragments at 64-80 and 112-116]
213-221	Olive green clay (shelly inclusions)
221-244	Peat (poorly humified + highly minerogenic) [wood fragments at 236-238]
244-268	Blue grey clay (angular clasts)
268-295+	Brown grey clay

Transect 1: Hole 7 (NX 263790 546064)

8.82m O.D.

0-10	Top soil
10-23	gritty soil
23-42	Medium/light brown silty clay
42-53	Peat (brown + poorly humified)
53-72	light brown silty clay
72-76	Peat - clay - peat
76-82	Light brown silty clay
82-225	Peat (Poorly humified) [wood fragments at 83-84, 164-169 and 218-220]
225-238	Green/brown marl (some OM + shelly inclusions)
238-262	Olive green marl
262-292	Green/brown marl (OM + shelly inclusions)
292-303	Peat (Poorly humified)
303-330	Grey blue clay (clasts)
330-350+	Brown grey clay

Transect 1: Hole 8 (NX 263807 546074)

8.92m O.D.

0-30	Top soil
30-53	Organic silt
53-67	Organic silt with plant remains
67-97	Dark grey/brown organic silty clay
97-260	Peat (poorly humified) [Carbonised wood fragment 152-160]
260-295	Peat becoming increasingly more silty toward base [wood fragment at 285-290]
295-306	light brown silty clay + OM [charcoal at 298-300]
306-313	light grey fine silty clay
313-317	light brown silty sand clay + OM
317-327+	Blue grey clay (silty + sandy + clasts)

Transect 1: Hole 9 (NX 263824 546084)

8.97m O.D.

0-46	Top soil
46-59	light grey/brown silty clay
59-105	light grey/brown silty clay + OM
105-197	Silty peat (poorly humified + wood throughout layer)
197-206	Alder wood fragment
206-260	Peat (brown + poorly humified + sedge peat)
260-285	Peat (black + well humified)
285-294+	Blue grey clay

Transect 1: Hole 10 (NX 263842 546094)

9.07m O.D.

0-28	Top soil
28-71	Mid-grey silty sand
71-76	Fine grey silty sand
76-94	Silty sand becoming increasingly more organic
94-180	Peat (dark + poorly humified) [wood fragment at 130]
180-230	Silt with varying degrees of organic content
230-239	Dark grey organic silty clay
239-273	Peat (dark + poorly humified)
273-285+	Grey blue clay (silt + sand)

Transect 1: Hole 11 (NX 263860 546104)
9.35m O.D.

0-15	Top soil
15-43	Dark grey silty clay
43-105	Light grey clay (charcoal fragments + mottling)
105-154	Organic silty clay [wood fragment at 114-120]
154-157	fine grey sand
157-211	Organic silty clay [wood fragment at 160-166]
211-239	highly organic silt (dark brown/grey)
239-282	light grey organic silt
282-289	Dark grey organic silt
289-291+	Blue grey clay (sand + angular clasts)

Transect 1: Hole 12 (NX 263878 546114)
9.47m O.D.

0-105	Light grey clay (mottling)
105-176	Dark grey organic silt with wood [fine grey sand layer at 152-153]
176-251+	Medium grey organic clay [wood fragment at 222-228)

Transect 2: Hole 1 (NX 263708 545999)
9.84m O.D.

0-168	Top soil + sand [Lumps of organic matter between 130-141] [Lump of dark brown humified peat at 149-157]
168-169	Peat
169-184	Dark grey clay (sandy + silty)
184-193	Silty clay sand (Brown)
193-209	sandy silt
209-227	Peat (Dark brown)
227-267	Peat (brown)
267-295	grey blue clay
295-310+	grey brown clay

Transect 2: Hole 2 (NX 263725 546010)
8.86m O.D.

0-25	Top soil
25-44	Medium/coarse sand + silt + OM
44-68	Peat (dark + humified)
68-83	Dark grey clay (sandy + silty)
83-94	Brown silty clay + OM
94-190	Peat (dark brown + poorly humified)
190-193	Dark brown organic silt
193-216	Grey blue clay (silty/sandy + angular clasts)
216-227+	Grey brown clay (silty)

Transect 2: Hole 3 (NX 263742 546022)
8.69m O.D.

0-83	Dark brown organic silty sand
83-190	Peat (Brown + poorly humified)
190-227	Brown/grey organic silt
227-252	Grey blue clay (silty/sandy + clasts)
252-266+	Grey brown clay

Transect 2: Hole 4 (NX 263761 546033)
8.66m O.D.

0-38	Brown organic silt
38-62	Light grey silty clay + OM
62-81	Brown organic silt
81-203	Peat (brown + poorly humified)
203-260	Olive green marl
260-273	Dark grey/green silt (transitional)
273-280	Dark grey organic silt
280+	Penetrated further but no sample recovered

Transect 2: Hole 5 (NX 263777 546041)
8.70m O.D.

0-41	Top soil
41-73	Dark grey silt (could require correction to clay???)
73-110	Dark brown organic silt
110-160	Peat (brown + poorly humified)
160-196	Dark Olive green marl
196-223	Peat (brown + poorly humified)
223-279	Light olive green marl
279-285	Dark olive green/brown silt
285-295	Dark olive green/brown silt + wood fragments (alder)
295+	Penetrated further but no sample recovered

Transect 2: Hole 6 (NX 263797 546049)
8.72m O.D.

0-15	Top soil
15-33	Brown/grey silty sand
33-47	Dark grey silty clay
47-52	Peat
52-68	Dark grey silty clay
68-78	Dark grey sand
78-167	Dark brown organic silt
167-242	Dark brown organic silt (increasingly more fibrous/peaty) [wood fragments at 215-227]
242-303	Olive green marl
303-323	Brown/grey organic silt
323-355	Brown silty peat
355-365+	Blue grey gritty clay

Transect 2: Hole 7 (NX 263816 546059)
8.79m O.D.

0-10	Top soil
10-62	Dark grey silty clay
62-107	Dark grey/brown organic silty/sand + wood fragments
107-111	Grey sand
111-195	Peat (brown + well humified)
195-258	Peat (brown + well humified + wood fragments)
258-319	Grey/brown organic silt (Greenish tinge) [wood fragment at 291-294]
319-329+	Blue grey gritty clay

Transect 2: Hole 8 (NX 263834 546068)
8.92m O.D.

0-9	Top soil
9-107	Grey silty clay (some mottling)
107-250	Peat (brown + silty) [charcoal/burnt wood at 135-136]
250-277	Grey/brown organic silt [wood fragment at 268-269]
277-295	Peat (dark grey/black + silty)
295-297+	Grey blue gritty clay

Transect 2: Hole 9 (NX 263852 546078)

9.14m O.D.	
0-27	Top soil
27-96	Grey silty clay (mottling)
96-127	Dark grey organic silt [some charcoal]
127-199	Dark brown organic silt [wood fragments at 153-154; 165-167 and 194-195] [grey sand 150-151]
199-207	Wood
207-282	Peat (dark brown + well humified)
282-315	Peat (dark brown/grey + well humified)
315-329+	Blue grey gritty clay

Transect 2: Hole 10 (NX 263870 546087)

9.32m O.D.	
0-23	Top soil
23-100	Grey silty clay (mottling)
100-132	Transitional: grey silty clay to organic silts
132-274	Brown/grey organic silt [grey sand trace at 264]
274-287	Grey silty clay
287	Solid

Transect 2: Hole 11 (NX 263888 546098)

9.58m O.D.	
0-24	Top soil
24-40	Grey silty clay (mottling)
40-68	Grey silty clay (heavily mottled)
68-133	Grey silty clay (mottling)
133-231	Dark grey/brown organic silt
231-239	Brown organic silt [some carbonised material]
239-264+	Dark grey silty clay

Transect 3: Hole 1 (NX 263881 546069)

9.41m O.D.	
0-25	Top soil
25-121	Grey silty clay (mottling)
121-137	Peat (dark brown + silty) [some charcoal]
137-158	Dark grey organic silt [wood fragment at 144-146]
158-175	Wood
175-200	Dark grey/brown organic silt
200	Prevented from further penetration due to wood (?)

Transect 3: Hole 2 (NX 263862 546061)

9.21m O.D.	
0-27	Top soil
27-91	Grey silty clay
91-95	Coarse grey sand
95-114	Brown grey organic silt
114-136	Wood
136-255	Peat (brown)
255-300	Brown/grey organic silt [wood fragment at 293-296]
300-326	dark grey silt
326-362+	Blue grey gritty clay

Transect 3: Hole 3 (NX 263846 546049)
9.14m O.D.

0-14	Top soil
14-105	Grey silty clay (mottling)
105-153	Dark grey organic silt
153-249	Peat (dark brown + silty) [wood fragments + charcoal at 243-245]
249-280	Brown organic silt
280-285	Wood
285-300	Dark grey silt
380-312+	Blue grey gritty clay

Transect 3: Hole 4 (NX 263829 546038)
8.80m O.D.

0-10	Top soil
10-120	Grey silty clay (mottling)
120-145	Dark grey organic silt
145-180	Dark brown peaty silt
180-270	Peat (dark brown)
270-300	Grey silt
300-320	Blue grey gritty clay
320-329+	Brown grey clay

Transect 3: Hole 5 (NX 263812 546027)
8.83m O.D.

0-8	Top soil
8-35	Grey brown silt
35-106	Grey silty clay (mottling)
106-123	Peat (dark grey/black) [grey silt at 111-118]
123-298	Peat (brown)
298-314	Dark grey silt (green tinge) [some wood fragments]
314-353	Dark grey brown silt + OM
353-356	Dark grey sand
356-376	Grey brown silt
376-385	Blue grey gritty clay
385-395+	Light grey/brown clay

Transect 3: Hole 6 (NX 263795 546016)
8.71m O.D.

0-8	Top soil
8-28	Grey silt
28-44	Sandy silt
44-106	Brown/grey organic silty clay
106-250	Peat (brown)
250-262	Olive green marl
262-263	Peat
263-264	Olive green marl
264-268	Peat
268-298	Olive green marl
298-315	Grey/brown silt + OM
315-339	Wood (carbonized?)
339-353	Grey silt
353-382+	Blue grey gritty clay

Transect 3: Hole 7 (NX 263779 546002)

8.73m O.D.	
0-8	Top soil
8-28	Dark grey silty sand
28-42	Grey silty clay
42-66	Peat (dark brown + silty)
66-117	Grey silty clay + OM
117-196	Peat (brown + silty)
196-236	Olive green marl
236-261	Dark grey organic silt
261-358	Olive green marl
358-412	Peat (brown + silty)
412-422	Grey silt
422-434+	Blue grey gritty clay

Transect 3: Hole 8 (NX 263759 546004)

8.75m O.D.	
0-20	Top soil
20-40	Dark grey sandy silt
40-107	Dark brown/grey organic silt
107-220	Peat (brown) [wood at 120-130]
220-268	Olive green marl
268-281	Peat (dark brown)
281-393	Olive green marl
393-396	Grey sand
396-470	Brown peaty silt
470-478	Grey silt
478-483+	Blue grey gritty clay

Transect 3: Hole 9 (NX 263734 545987)

9.47m O.D.	
0-13	Top soil
13-62	Grey sandy silt
62-70	Grey sand with peat
70-84	Dark grey medium/coarse sand
84-152	Peat (Brown)
152-246	Peat (grey/brown + silty)
246-275	Coarse/medium grey sand
275-283	Peat (dark grey + silty)
283-290	Olive green marl
290-297	Dark grey organic silt
297-310	Olive green marl
310-340	Peaty silt (gyttja?)
340-406	Olive green marl
406-425+	Blue grey gritty clay

Transect 3: Hole 10 (NX 263723 545984)

9.84m O.D.	
0-30	Top soil
30-80	Grey sandy silt
80-107	Grey sand (shelly)
107-182	Peat (brown)
182-223	Grey organic silt
223-266	Peat (brown)
266-298	Blue grey coarse/medium sand
298-318	Olive green silt + OM (shells)
318-321	Blue grey sand
321-354	Olive green marl
354-358	Peat

358-416	Olive green marl
416-426	Gritty blue grey clay + angular clasts
426-440+	Blue grey clay

Transect 4: Hole 1 (NX 263737 545970)

10.20m O.D.	
0-10	Top soil
10-60	Brown sandy silt
60-158	Grey shelly sand [sharp change in colour at 115 to blue/grey]
158-260	Peat (brown)
260-310	Brown/grey organic silt [wood fragments]
310-443	Peat (brown)
443-466	Blue grey silty sand
466-512	Olive green organic silt (some shells)
512-520	Blue grey coarse/medium sand (with shells)
520-558	Olive green marl
558-562	Blue grey coarse/medium sand (with shells)
562-626	Olive green marl
626-645	Peat (brown)
645-660	Grey silt
660-666+	Blue grey gritty clay

Transect 4: Hole 2 (NX 263755 545982)

9.20m O.D.	SAMPLE HOLE
0-10	Top soil
10-33	Sandy silt
33-51	Light grey sand
51-60	Peat
60-66	Dark grey blue sand
66-109	Peat
109-142	Grey silt
142-170	Peaty silt
170-199	Grey silty clay
199-306	Peat (brown)
306-316	Grey blue sand
316-378	Olive green organic silt
378-498	Olive green marl [Blue grey medium/coarse sand layers at 408-410 and 468-470]
498-556	Peat (brown + silty + sandy) [wood fragment at 540-544]
556-559	Peat (brown + silty)
559-571+	Grey blue clay

Transect 4: Hole 3 (NX 263770 545993)

8.82m O.D.	
0-23	Top soil
23-68	Grey organic silt
68-76	Light grey sandy silt
76-112	Brown silt
112-207	Peat (brown + silty)
207-211	Blue sand
211-228	Brown silt
228-295	Olive green marl [wood fragment at 231-235 + possible sand layers at 208 and 226]
295-318	Dark olive green gyttja
318-436	Olive green marl
436-472	Peat (brown + silty) [wood fragments]
472-481	Wood
481-482+	Blue grey gritty clay

Transect 4: Hole 4 (NX 263795 545992)
8.86m O.D.

0-28	Top soil
28-100	Grey silty clay with mottling
100-118	Peat (Brown + silty)
118-122	Grey silty clay
122-198	Peat (brown + silty) [wood fragment at 127-129)
198-264	Dark olive green organic silt
264-296+	Blue grey clay

Transect 4: Hole 5 (NX 263813 546004)
8.85m O.D.

0-8	Top soil
8-85	Grey silty clay
85-161	Peat (brown + silty)
161-171+	Blue grey gritty clay

Transect 4: Hole 6 (NX 263829 546015)
8.95m O.D.

0-86	Grey silty clay (mottling)
86-162	Peat (brown + silty)
162-168+	Blue grey gritty clay

Transect 4: Hole 7 (NX 263841 546019)
9.01m O.D.

0-84	Grey silty clay (mottling)
84-107	Grey organic silt
107-113	Wood
113-177	Peat (dark brown)
177-180	Blue grey gritty clay
180-196+	Brown grey clay

Transect 4: Hole 8 (NX 263864 546032)
9.19m O.D.

0-91	Grey silty clay (mottling)
91-173	Peat (brown + silty)
173-186	Grey silt
186-189	Blue grey gritty clay
189-196+	Brown grey clay

Transect 4: Hole 9 (NX 263881 546045)
9.08m O.D.

0-54	Grey silty clay (mottling)
54	Did not penetrate any further due to solid

Transect 5: Hole 1 (NX)
9.24m O.D.

0-40	Grey silty clay (mottling)
40	Did not penetrate any further due to solid

Transect 5: Hole 2 (NX 263859 546007)
9.05m O.D.

0-82	Silty grey clay (mottling)
82-131	Peat (dark grey + silt)
131-141	Blue grey gritty clay
141-146+	Light grey brown blue clay

Transect 5: Hole 3 (NX 263839 545994)
9.00m O.D.

0-89	Grey silty clay
89-155	Peat (dark grey/brown)
155-191+	Blue grey gritty clay

Transect 5: Hole 4 (NX 263823 545986)
9.01m O.D.

0-74	Grey silty clay (mottling)
74-90	Dark grey organic silt
90-203	Peat (dark brown)
203-245+	Blue grey gritty clay

Transect 5: Hole 5 (NX 263805 545976)
9.25m O.D.

0-36	Grey silty sand
36-48	Grey shelly sand
48-124	Grey silty clay (high OM content between 48-60)
124-162	Grey organic silt
162-164	Wood
164-268	Peat (dark brown)
268-293+	Blue grey gritty clay

Transect 5: Hole 6 (NX 263788 545965)
9.96m O.D.

0-54	Light brown silty sand
54-77	Light grey shelly sand
77-85	Dark grey silty sand
85-109	Shelly sand
109-115	Grey silty sand
115-129	Shelly sand
129-169	Peat (brown + silt)
169-180	Grey organic silt
180-199	Brown/grey organic silt
199-245	Grey silty clay [blue grey clay at 222-229]
245-328	Peat (dark brown)
328-378	Light olive green marl
378-436	Dark olive green gyttja
436-480	Light olive green marl
480-490	Dark grey silt
490-495+	Blue grey gritty clay

Transect 5: Hole 7 (NX 263769 545955)
10.43m O.D.

0-46	Brown silty sand
46-77	Grey shelly sand

Too much sand to allow further penetration

Transect 6: Hole 1 (NX 263835 55969)
9.34m O.D.

0-33	Grey silty sand
33-63	Grey silty clay (mottling)
63-81	Grey brown organic silt
81-114	Light grey clay
114-127	Light grey very fine sand and silt
127-169	Peat (brown)
169-178+	Blue grey gritty clay

Transect 6: Hole 2 (NX 263851 5445981)
9.27m O.D.

0-25	Grey silt
25-64	Grey silty clay (mottling)
64	Solid (possibly a sub-surface rock ridge)

Transect 6: Hole 3 (NX 263867 545992)
9.14m O.D.

0-26	Grey silt
26-46	Grey silty clay (mottling) [blue grey tinge at base]
46	Solid (rock ridge?)

Transect Y: Hole 1 (NX 263925 546152)
9.85m O.D.

0-65	Grey silty clay (mottling)
65-90	Organic silty clay with coarse sand
90-138	Blue grey coarse sand (fine and coarse gravel)
138-151	Brown peaty organic silt
151-220	Blue grey coarse sand (fine and coarse gravel)
220-246+	Grey clay + angular clasts

Transect Y: Hole 2 (NX 263951 546188)
10.29m O.D.

0-78	Grey silty clay
78-89	Brown organic silty sand
89-110	Grey silty clay
110-126+	Blue grey sandy clay

Transect Y: Hole 3 (NX 263990 546233)
10.60m O.D.

0-55+	Grey silty clay (mottling)
	Angular clasts at base

Transect Y: Hole 4 (NX 264026 546294)
11.02m O.D.

0-85	Gley
85-90+	Grey gritty sand and gravel (Silt + clay)

Transect Z: Hole 1 (NX 263787 546027)
8.67m O.D.

0-33	Peat (brown + silty)
33-114	Grey silty clay
114-145	Peat (brown)
145-152	Dark olive green organic silt (shelly)
152-163	Peat (brown)
163-198	Olive green marl
198-220	Dark olive green organic silt
220-236	Peat (dark brown)
236-320	Light olive green marl
320-386	Peat (brown + silty)
386-395+	Blue grey gritty clay

Transect Z: Hole 2 (NX 263773 546015)

8.67m O.D.

0-35	Grey sandy silt
35-109	Grey/brown organic silty clay
109-177	Peat (brown + silty) [wood fragment at 145-148]
177-235	Light olive green marl
235-245	Peat (brown)
245-340	Light olive green marl
340-341	Grey blue fine sand
341-437	Peat (brown + silty)
437-439	Blue grey fine sand
439-453	Peat (brown + silty)
453+	Blue grey gritty clay

Transect D: Hole 1 (NX 263756 545912)

11.37m O.D.

0-15	Top soil
15-240	Brown shelly sand
240-260	Grey sand
260-267	Grey sand with lenses of peat
267-275	Dark humified peat
275-316	Grey sand + peat layers + OM (phragmites)
316-380	Blue grey sand
380-419	Peat (humified but becoming increasingly more silty in last 5cm)
419-425	Peaty silt
425-437	Peat (compact)
453-478	Grey organic silty clay
478-552	Peat (compact)
552-557	Gyttja
557-562	Dark blue grey gritty sand
562-573	Gyttja (dark silty peat)
573-577	Grey blue sand with peat layer
577-590	Gyttja/silty peat [sand layers at 589-590 and 585]
590-612	Grey blue sand
612-634	Organic silt/gyttja [sand layers at 621-622 and 633-634]
634-668	Blue grey coarse sand

Did not penetrate any further due to sand slumping into hole

Brighouse Bay Foreshore (BB/F)

BB/F 1 (NX 63485 45432)

2.92m O.D.

0-130	Beach sand (coarse)
130-145	Peat smear
145-158	Very dry dark brown well humified peat
158+	Blue grey silt, sand, clay and gravel matrix

BB/F 2 (NX 63460 65408)

2.50m O.D.

0-185	Dark grey coarse shelly beach sand
185-193	Grey/brown organic silt and sand
193-220	Compact dark brown well humified peat
220-222+	Grey clay

BB/F 3 (NX 63441 45376)

2.25m O.D.

0-158	Dark grey coarse shelly beach sand
158-163	Dark brown/grey silty clay + shell fragments
163-167	Light brown (silty?) peat
167-214	Dark brown/black well humified compact peat with occasional wood and fibres

BB/F 4 (NX 45338 63414)

1.49m O.D.

0-120	Coarse blue/grey beach sand
120-178	Peat (disturbed recovery during coring)
178-201	Dark brown well humified peat
201-225+	Blue/grey sandy gravel

Appendix E

Borehole records for the Cree estuary

Information provided for each borehole includes site code and borehole number, national grid reference (either 8 or 10 figure reference, height of borehole surface (m O.D.) and stratigraphical descriptions (depth in centimetres).

Palnure (PAL)

PAL 1 (NX 44960 63735)
11.94m O.D.

0-10	Black well humified peaty top soil
10-390	Red brown well humified fibrous peat (more wood in 300-390)
390-420	Brown/grey organic clay with Phragmites
420-431	Brown well humified woody peat (contamination?)
431-448	Brown/grey organic clay with Phragmites
448-459	Blue/grey silty clay with some organics
459-471	Contaminated
471-600	Blue/grey silty clay (Organic rich Phragmites layer at 553-559)
600	Hit solid

PAL 2 (NX 44955 63720)
11.65m O.D.

0-63	Black well humified peaty top soil with wood
63-387	Red/brown fibrous wood peat (large wood pieces between 328-387)
387-413	Brown/grey organic clay
413-1203	Blue/grey silty clay with Phragmites
1203-1216	Brown/blue/grey organic clay
1216-1223	Dark brown compact well humified peat
1223-1224	Band of Blue/grey silty clay
1224-1228+	Dark brown compact well humified peat

PAL 3 (NX 44950 63705)
11.37m O.D.

0-49	Black well humified peaty top soil
49-200	Red/brown fibrous woody peat
200-336	Red/brown fibrous peat with sedge and wood fragments
336-405	Brown/grey very organic clay with Phragmites
405-1193	Blue/grey silty clay
1193-1200+	Dark brown well humified peat

PAL 4 (NX 44940 63690)
11.07m O.D.

0-66	Black well humified peaty top soil
66-300	Red brown fibrous peat
300-338	Brown/grey organic clay with wood and Phragmites
338-1185	Blue/grey silty clay with Phragmites in top three metres
1185-1197	Brown/grey organic silty clay
1197-1215+	Dark/brown well humified compact peat

PAL 5 (NX 44930 63670)
10.93m O.D.

0-20	Very dry peaty top soil
20-72	Black well humified peat (wood at 55 and Eriophorum between 43-72)
72-300	Red/brown well humified fibrous peat with wood at 245, 266 and 292
300-312	Very organic brown/grey clay with Phragmites
312-1226	Blue/grey silty clay with Phragmites
1226-1268	Dark brown compact well humified peat
1268-1276+	Dark grey dry clay

PAL 6 (NX 44905 63630)
9.26m O.D.

0-15	Brown/grey organic clay top soil
15-63	Dark brown well humified peat
63-90	Grey silty clay
90-95	Dark brown peat (contamination ?)
95-111	Brown/grey silty organic clay
111-1056	Blue/grey silty clay (more organics and Phragmites between 403-417)
1056-1063	Brown/grey organic silts
1063-1070	Dark brown compact peat
1070-1079	Brown/grey organic clay
1079-1105+	Grey silty clay

PAL 7 (NX 44900 63620)
No altitude taken (stratigraphy uncertain - continuous contamination)

0-72	Organic clay top soil
72-82	Grey clay
82-86	Organic brown/grey clay
86-104	Dark brown well humified peat (contamination?)
104-130	Brown/grey organic clay
130-200+	Blue/grey silty clay

PAL 8 (NX 44890 63590)
No altitude taken (stratigraphy uncertain - continuous contamination)

0-41	Black well humified peaty top soil
41-44	Grey organic silty clay
44-47	Dark brown silty peat
47-65	Brown/grey organic clay
65+	Blue/grey silty clay with phragmites

Muirfad Flow (MF)

MF 1 (NX 4598 6238)
12.23m O.D.

0-50	Dark brown Sphagnum peat (compact) with roots and fibres
50-203	Orange/brown to red brown Sphagnum peat
203-302	Dark brown well humified peat with wood fragments
302-400+	Blue/grey silty clay with wood in top 20cm

MF 2 (NX 4590 6234)
12.02m O.D.

0-12	Black well humified peat
12-200	Orange/brown to red brown Sphagnum peat
200-258	Dark brown well humified Sphagnum peat with wood fragments
258-273	Light brown Sphagnum well humified peat with Phragmites
273-300+	Blue/grey silty clay

MF 3 (NX 4582 6231)
12.15m O.D.

0-25	Black well humified Sphagnum peat
25-100	Orange/brown fibrous Sphagnum peat
100-200	Red/brown Sphagnum peat with fibres and Eriophorum
200-302	Dark brown well humified peat with some Eriophorum and wood
302-400+	Blue/grey silty clay

MF 4 (NX 4574 6228)
12.36m O.D.

0-117	Orange/brown Sphagnum peat
117-221	Dark brown sloppy Sphagnum peat with wood
221-228	Brown/grey silty peat
228-300+	Blue/grey silty clay

MF 5 (NX 4566 6225)
12.65m O.D.

0-10	Black well humified peat
10-200	Orange/brown Sphagnum peat
200-300	Red/brown Sphagnum peat
300-400	No sample recovered
400-500+	Blue/grey silty clay

MF 6 (NX 4558 6221)
12.67m O.D.

0-10	Black well humified peat
10-220	Orange/brown Sphagnum peat
220-379	Dark brown well humified peat with Phragmites at 369-379
379-388	Brown/grey organic clay
388-400+	Blue/grey silty clay

MF 7 (NX 4550 6218)
11.66m O.D.

0-40	Black well humified peat
40-344	Orange/brown Sphagnum peat with wood fragments
344-400+	Blue/grey silty clay

MF 8 (NX 4542 6215)
10.43m O.D.

0-20	Dark brown Sphagnum peat
20-115	Orange/brown Sphagnum peat
115-204	Black Sphagnum peat
204-300	Dark brown well humified fibrous peat with Eriophorum and wood
300-400+	Blue/grey silty clay

MF 9 (NX 4534 6212)
9.98m O.D.

0-15	Dark brown Sphagnum peat
15-100	Compact brown Sphagnum peat
100-249	Dark brown well humified fibrous peat with Eriophorum
249-256	Brown/grey organic clay with wood fragments
256-300+	Blue/grey silty clay

MF 10 (NX 4527 6209)
9.70m O.D.

0-20	Dark brown well humified peat
20-120	Orange/brown to dark brown compact Sphagnum peat
120-263	Dark brown well humified peat with wood in lower half
263-300+	Blue/grey silty clay

MF 11 (NX 4568 6216)
12.55m O.D.

0-20	Dark brown well humified peat
20-200	Orange/brown Sphagnum peat with Eriophorum between 100-200
200-343	Dark brown well humified peat with Eriophorum and Sphagnum
343-400+	Blue/grey silty clay

MF 12 (NX 4569 6207)
11.92m O.D.

0-12	Dark brown well humified peat
12-100	Orange/brown compact Sphagnum peat
100-220	Red/brown Sphagnum peat with Eriophorum
220-290	Dark brown well humified peat with wood fragments
290-310	Brown/grey very organic clay
310-400+	Blue/grey silty clay

MF 13 (NX 4565 6233)
12.32m O.D.

0-12	Dark brown well humified peat
12-200	Orange/brown Sphagnum peat
200-288	Dark brown well humified peat with Sphagnum
288-348	Dark brown well humified peat with Sphagnum and wood
348-400+	Blue/grey silty clay

Carsewalloch Flow (CWF)

CWF 1 (NX 4573 6152)
11.21m O.D.

0-60	Dark brown well humified Sphagnum peat with roots and fibres
60-215	Orange/brown to red/brown Sphagnum peat with fibres
215-262	Dark brown well humified peat
262-285	Brown/grey organic clay
285-300+	Blue/grey silty clay

CWF 2 (NX 4581 6156)
12.44m O.D.

0-200	Brown Sphagnum peat with fibres and roots
200-232	Dark brown Sphagnum peat and fibres
232-400	Black well humified Sphagnum peat with wood
400-500+	Blue/grey silty clay

CWF 3 (NX 4589 6160)
12.43m O.D.

0-100	No sample recovered (peat)
100-381	Brown fibrous Sphagnum peat with wood
381-400+	Blue/grey silty clay

CWF 4 (NX 4596 6164)
12.13m O.D.

0-229	Light brown to Orange brown Sphagnum peat with fibres and roots
229-306	Dark brown/black well humified Sphagnum peat with fibres
306-325	Black well humified peat with wood fragments
325-333	Brown/grey peaty clay with wood
333-400+	Blue/grey silty clay

CWF 5 (NX 4603 6168)
12.40m O.D.

0-100	No sample recovered
100-150	Orange/brown Sphagnum peat with fibres
150-310	Brown Sphagnum peat
310-359	Black well humified peat with wood
359-364	Brown/grey peaty clay with wood
364-400+	Blue/grey silty clay

CWF 6 (NX 4611 6172)
10.20m O.D.

0-127	Brown very compact Sphagnum peat with fibres and wood
127-136	Grey organic clay
136-142	Brown/grey peaty clay
142-200+	Blue/grey silty clay

CWF 7 (NX 4608 6180)
10.18m O.D.

0-109	Dark brown compact Sphagnum peat with fibres
109-200+	Blue/grey silty clay

CWF 8 (NX 4600 6176)
10.26m O.D.

0-116	Dark brown compact Sphagnum peat with fibres and wood
116-128	Grey organic clay
128-137	Brown peat with clay
137-200+	Blue/grey silty clay with wood in top 20

CWF 9 (NX 4593 6171)
10.88m O.D.

0-173	Brown to orange/brown compact Sphagnum peat with fibres
173-200	Black/dark brown well humified peat
200-300+	Blue/grey silty clay

CWF 10 (NX 4585 6168)
11.00m O.D.

0-205	Brown to orange brown compact Sphagnum peat with Eriophorum and wood
205-223	Brown well humified peat with wood
223-300+	Blue/grey silty clay

CWF 11 (NX 4578 6164)
11.70m O.D.

0-100	Brown to Orange/brown Sphagnum peat with fibres and roots
100-227	Brown sloppy Sphagnum peat
227-304	Dark brown well humified Sphagnum peat with wood and Eriophorum
304-310	Grey organic clay
310-400+	Blue/grey silty clay

CWF 12 (NX 4570 6160)
10.57m O.D.

0-118	Dark brown compact Sphagnum peat with fibres
118-186	Dark brown well humified peat
186-207	Wood
207-216	Dark brown well humified peat
216-300+	Blue/grey silty clay

CWF A (NX 46095 61805)
10.22m O.D.

0-113	Brown <u>Sphagnum</u> peat
113-1057	Blue/grey silty clay
1057-1068	Brown/grey organic clay
1068-1075	Brown compact well humified peat
1075-1700+	Dark grey silty clay with occasional black mottling

CWF B (NX 45905 61700)
10.97m O.D.

0-213	Dark brown well humified peat with wood
213-1600+	Blue/grey silty clay to grey clay (possibly more organic at *circa* 1000)

Blairs Croft (BC)

BC/1/1 (NX 46385 61920)
11.10m O.D.

0-50	Top soil
50	Solid (gravel)

BC/1/2 (NX 46378 61915)
10.91m O.D.

0-66	Dark brown/black peaty top soil (clay content at 59-66)
66-94	Blue/grey silty clay with wood
94-97	Dark brown dry peat
97-110	Light grey fine sand and stones with wood in top
110	Solid (?)

BC/1/3 (NX 46373 61913)
10.66m O.D.

0-44	Dark brown/black peaty top soil
44-69	Blue/grey silty clay with wood
69-90	Brown/grey peaty clay with wood
90-112	Brown/grey organic silty clay
112-117+	Dark blue/grey sandy clay with stones

BC/1/4 (NX 46380 61918)
10.95m O.D.

0-51	Dark brown/black peaty top soil
51-59	Brown/grey organic clay
59-72	Blue/grey silty clay
72-88	Dark brown compact well humified peat
88	Solid

BC/1/5 (NX 46368 61910)
10.53m O.D.

0-31	Dark brown/black peaty top soil
31-70	Blue/grey silty clay
70-93	Brown/grey organic clay with wood
93-103	Brown compact well humified peat
103-140	Grey organic silty sandy clay with wood
140+	Trace of blue/grey fine sand and stones but hit solid (stones)

BC/1/6 (NX 46355 61900)
10.05m O.D.

0-44	Dark brown peaty top soil
44-66	Wood
66-96	Dark brown sloppy sphagnum peat
96-105	Brown/grey organic clay with wood
105-117	Sloppy - no sample recovered
117-165	Blue/grey silty clay with wood
165-180	Grey organic clay with wood and Phragmites
180-200	Brown/grey sloppy organic clay
200-227	Brown/grey organic clay with Phragmites
227-243	Blue/grey silty clay
243-250	Brown/grey organic clay
250-287	Blue/grey silty clay
287-300	Sloppy clay (poor recovery)
300-400	Blue/grey silty clay with wood and Phragmites
400-421	Brown/grey peaty clay with wood
421-444	Grey organic clay
444-600	Blue/grey silty clay
600+	Gravel/sand ? (no sample retrieved)

BC/1/7 (NX 46305 61868)
9.24m O.D.

0-43	Dark brown well humified peat
43-200+	Blue/grey silty clay with wood and Phragmites

BC/1/8 (NX 46240 61825)
9.22m O.D.

0-32	Dark brown top soil
32-38	Light grey clay (very dry)
38-100+	Blue/grey silty clay

BC/2/1 (NX 46385 61988)
11.74m O.D.

0-55	Dark brown peaty top soil
55-70	Brown/grey compact organic silty clay with stones
70-75	Light grey sand and stones
75-82	Brown/grey organic sand
82-131	Orange/brown sand
131+	Solid

BC/2/2 and 3 (NX 46375 61982)
11.20m O.D.

0-51	Black peaty top soil
51-57	Light brown clay
57-68	Grey sand with stones
68-72	Black peaty soil
72-75	Light grey sand with stones
75-83	Nothing recovered
83-100	Light grey sandy clay

BC/2/4 (NX 46362 61975)
10.65m O.D.

0-42	Black peaty top soil
42-61	Light blue/grey silty clay
61-82	Black well humified peat with wood
82-104	Brown/grey clay with wood
104-149	Brown/grey peaty clay
149-155	Grey/brown organic clay with Phragmites
155-158	Grey sandy clay with stones
158-164	Wood
164+	Solid/grey gravel

BC/2/5 (NX 46340 61965)
10.06m O.D.

0-42	Black peaty top soil
42-108	Dark brown fibrous peat with wood
108-123	Light grey/brown peaty clay with wood
123-158	Brown/grey organic clay
158-174	Light blue grey silty clay
174-221	Brown/grey organic clay
221-238	Brown well humified peat with some clay and wood
238-257	Light brown/grey clay with Phragmites
257-264	Brown well humified peat
264-310	Light brown/grey clay with Phragmites
310-434	Blue/grey silty clay with wood and Phragmites
434-465	Brown peaty clay with wood
485-700+	Blue/grey silty clay

BC/2/7 (NX 46290 61939)
9.84m O.D.

0-90	Black/dark brown well humified compact peat with wood between 70 and 90
90-126	Light grey clay with wood and Phragmites
126-144	Dark blue/grey gravel
144-151	Yellow shell layer
151-165	Dark blue/grey silty clay
165-200+	Blue/grey silty clay

BC/2/8 (NX 46210 61901)
10.77m O.D.

0-55	Dark brown/black well humified peat
55-200+	Blue/grey silty clay

BC/3/1 (NX 46365 61958)
11.37m O.D.

0-55	Dark brown/black clayey top soil
55-64	Brown/grey silty clay
64-72+	Green/grey sand/stones/clay matrix (no further)

BC/3/2 (between 1 & 7)
11.10m O.D.

0-44	Dark brown/black top soil
44-59	Dark brown peat
59-76	Blue/grey silty clay with wood
76-96	Brown/grey clay
96-106+	Green/grey sand/stones/clay matrix (no further)

BC/3/3 (between 1 & 7)
10.83m O.D.

0-37	Dark brown/black top soil
37-80	Brown/grey silty clay with wood
80-132	Brown organic silt with wood
132-148+	Dark blue/grey coarse sand and gravel (no further)

BC/3/4 (between 1 & 7)
10.70m O.D.

0-44	Dark brown/black top soil
44-75	Brown/grey clay
75-78	Dark brown organic silt
78-83	Brown/grey oragnic clay with wood
83-97	Brown compact well humified silty peat
97-111	Brown/grey organic clay
111-142	Brown silty woody peat
142-168+	Blue/grey coarse sand/stones/clay matrix (no further)

BC/3/5 (between 1 & 7)
10.50m O.D.

0-39	Dark brown well humified peat
39-80	Blue/grey silty clay with wood
80-98	Dark brwon well humified organic silt
98-102	Brown/grey organic clay
102-114	Brown organic silt
114-118	Blue/grey silty clay with wood
118-149	Brown woody peat
149-156	Blue/grey silty clay with wood
156-188	Brown woody peat
188-215	Brown/grey organic clay with wood
215+	Solid (gravel)

BC/3/6 (between 1 & 7)
10.38m O.D.

0-45	Brown fibrous peat
45-92	Blue/grey silty clay with wood
92-113	Brown silty clay with Phragmites
113-126	Brown organic fibrous silt
126-132	Brown organic clay
132-168	Brown silty peat with wood and fibres
168-200	Blue/grey silty clay with wood
200-240	Blue/grey silty clay
240-260+	Grey sand and gravel (no further)

BC/3/7 (NX 46337 61938)
10.13m O.D.

0-100	Brown well humified peat
100-146	Brown/grey clay with wood
146-210	Brown organic silt with wood
210-255	Brown/grey organic clay with wood
255-260	Brown organic silt
260-403	Blue/grey silty clay with wood
403-434	Brown Phragmites peat
434-443	Brown/grey clay
443-667	Blue/grey silty clay with Phragmites
667	Solid (gravel)

BC/3/8 (NX 46295 61909)
9.54m O.D.

0-60	Dark brown/black well humified peat
60-225	Blue/grey silty clay with wood
225-236	Brown/grey organic silt with Phragmites
236-951	Blue/grey silty clay with Phragmites
951-960+	Brown well humified compact peat with wood (no further)

BC/3/9 (NX 46235 61865)
9.75m O.D.

0-27	Brown peat
27-980	Blue/grey silty clay with occasional mottling
980-985+	Brown well humified compact peat (no further)

BC/4/1 (NX 46375 62233)
9.89m O.D.

0-45	Peaty dark brown top soil
45-113	Dark brown well humified peat
113-125	Light brown organic clay (slope wash?)
125-184	Woody dark brown well humified peat
184-192	Light brown organic clay (slope wash?)
192-200	Woody dark brown well humified peat
200-209	Very organic grey/brown clay
209-215	Brown well humified woody peat
215-256	Very organic grey clay with plant fibres (wood at 250-252; Phragmites at 230-240)
256-302	Blue/grey clay
302-314	Well humified brown fibrous peat
314-343	Very organic fibrous clay
343-370	Organic dark grey silty sand

BC/4/2 (NX 46365 62228)
9.73m O.D.

0-82	Dark brown well humified peat (wood at 23-25 and 52-53; rootlet at 72)
82-168	Orange brown fibrous Sphagnum peat (wood at 90, 123-125 and 191; charcoal at 160-161) [143-166 = light grey very organic clay with lenses at 144, 148 and 154]
168-242	Brown fibrous peat (wood at 208 and 225-230; Phragmites at 216)
242-265	Grey organic clay with Phragmites and wood
265-280	Brown/grey silty peat
280-379	Grey organic clay transitional to Blue/grey silty clay with organic fleks and Phragmites
379-393	Light brown wood peat
393-399	Very light brown (transitional) organic rich silt with fibres
399-440	Grey organic clay with Phragmites at 403-409 and 412-420
440-846	Blue/grey silty clay (occasional Phragmites)
846-890	Red/brown dry well humified peat with wood and Phragmites at 890
890-900	Dark grey/brown dry well humified peat with sand inclusions and some Phragmites
900-953	Dark grey coarse sands and gravels
953+	Hit solid (bedrock?)

BC/4/3 (NX 46355 62223)
9.73m O.D.

0-273 (slope	Dark brown/red well humified peat (wood at 71 and 58; Organic light grey clay wash?) at 136-148, 156-160, 174-185, 250-256 and 240-246)
273-300	Blue/grey silty clay
300-305	Light brown well humified organic clay
305-400	Blue/grey silty clay (Phragmites at 305-350)
400-410	Dark brown well humified fibrous peat
410-449	Organic rich grey clay with Phragmites
449-713	Blue/grey silty clay with Phragmites
713-717	Light brown Phragmites peat with some clay content
717-1007	Blue/grey silty clay
1007-1050	Red/brown very dry well humified peat
1050-1060	Very organic brown/grey clay
1060+	Could not penetrate any further as too tough

BC/4/4 (NX 46340 62215)
9.57m O.D.

0-63	Black well humified peat
63-162	Red/brown fibrous peat with Phragmites
162-171	Wood
171-236	Very organic fibrous blue/brown clay
236-267	Brown well humified peat (some minerogenics and wood)
267-337	Blue/grey organic fibrous clay
337-418	Blue/grey organic clay
418-439	Green/grey/brown very organic silt with wood fragments
439-1010	Blue/grey silty clay with Phragmites
1010-1014	Brown/blue/grey organic clay
1014-1032	Dark red/brown well humified compact peat
1032	Stopped as too tough

BC/4/5 (NX 46320 62208)
9.72m O.D.

0-83	Black well humified peat + roots
83-210	Red brown well humified peat
210-262	Brown/grey organic clay
262-267	Blue/grey clay with fibres
267-305	Brown/grey organic clay
305-313	Dark grey well humified peat with Phragmites
313-376	Brown/grey organic clay
376-1038	Blue/grey silty clay with Phragmites
1038-1044	Organic brown/grey clay with wood
1044-1055	Dark brown compact peat
1055	Stopped as too tough

BC/4/6 (NX 46280 62190)
10.00m O.D.

0-75	Black well humified dry peat
75-200	Red/brown well humified peat with wood
200-1067	Blue/grey silty clay with Phragmites
1067-1075	Brown compact well humified peat
1075	Stopped as too tough

BC/5/1 (NX 46400 62155)
11.37m O.D.

0-16	Dark brown peaty top soil
16	Hit solid

BC/5/2 (NX 46392 62153)
10.85m O.D.

0-226	Dark brown well humified peat with occasional wood fragments
226-234	Brown/grey organic silt
234-253	Dark brown well humified peat
253-272	Brown grey organic silt
272-324	Dark brown well humified peat
324-337	Light brown fibrous silty peat
337-347	Brown/grey organic silt
347-388	Dark brown sloppy well humified peat (some fibres)
388-417	Light brown/grey organic silt
417-444	Blue/grey silty clay with wood
444-448	Brown grey organic silt
448-467	Brown well humified peat with wood
467-514	Brown/grey silt (banded organic/minerogenic rich layers; wood at 470-485)
514-556	Blue/grey silty clay
556-570	Not recovered
570	Hit solid

BC/5/3 (NX 46383 62150)
10.61m O.D.

0-239	Dark brown well humified fibrous peat
239-264	Grey/brown organic silt
264-274	Dark brown peat with wood
274-290	Grey/brown organic silt
290-336	Dark brown well humified peat with wood
336-370	Grey/brown organic silt
370-406	Blue/grey organic clay
406-413	Dark brown well humified peat
413-490	Blue/grey silty clay with wood and Phragmites
490-510	Dark brown well humified peat with wood
510-539	Brown/grey organic silt (banded organic /minerogenic rich layers)
539-658	Dark brown well humified peat (contamination?)
658-815	Blue/grey silty clay
815	Hit solid (gravel?)

BC/5/4 (NX 46372 62148)
10.42m O.D.

0-258	Dark brown well humified fibrous peat with wood
258-283	Brown grey organic silt
283-300	Dark brown well humified peat
300-329	Brown/grey organic silt with wood
329-371	Dark brown well humified peat with wood
371-421	Brown/grey organic silt with wood
421-426	Dark brown well humified peat
426-511	Blue grey (organic) silty clay with wood
511-542	Dark brown well humified peat
542-575	Brown/grey (banded) organic silty clay
575-722	Blue/grey silty clay
722-729	Dark brown well humified peat
729-1000+	Blue/grey silty clay

BC/5/5 (NX 46363 62145)
10.25m O.D.

0-220	Dark brown well humified peat with wood
220-222	Brown/grey organic silt
222-267	Dark brown well humified peat with wood
267-345	Brown/grey organic silt (banded) with wood
345-356	Dark brown well humified peat with wood
356-370	Brown/grey organic silt (banded) with Phragmites
370-425	Grey/brown organic silty clay
425-430	Dark brown well humified peat
430-503	Blue/grey silty clay
503-522	Dark brown well humified peat (siltier to base)
522-562	Brown/grey organic silty clay (banded)
562-700+	Blue/grey silty clay

BC/5/6 (NX 46342 62138)
10.14m O.D.

0-236	Dark brown well humififed fibrous peat
236-266	Brown/grey peaty silt
266-331	Brown/grey organic silty clay with Phragmites
331-347	Brown/grey very organic silty clay with Phragmites and wood
347-351	Dark brown well humified fibrous peat
351-361	Brown silty peat
361-373	Brown/grey very organic silty clay with Phragmites and wood
373-420	Blue/grey silty clay with organics
420-433	Dark brown sloppy peat (contamination?)
433-500	Brown/grey organic clay
500-505	Brown/grey very organic silt
505-600	Grey organic clay
600-700+	Blue/grey silty clay

BC/5/7 (NX 46324 62133)
10.01m O.D.

0-209	Dark brown well humififed peat with wood
209-235	Brown/grey organic silt with Phragmites
235-269	Grey organic clay with Phragmites
269-280	Brown very organic silt with wood
280-315	Grey/brown organic clay with Phragmites
315-332	Brown peaty silt with Phragmites and wood
332-339	Brown well humified silty peat
339-346	Brown/grey organic silty clay
346-459	Blue/grey silty clay with Phragmites and wood
459-466	Brown well humified silty peat
466-476	Brown/grey organic silt
476-600+	Blue/grey silty clay

BC/6/1 (NX 46393 62145)
11.48m O.D.

0-58	Dark brown peaty top soil
58-65	Wood fragment
65-90	Black bery organic silt
90+	Solid

BC/6/2 (NX 46383 62144)
11.19m O.D.

0-150	Dark brown well humified peat with wood and fibres
150-163	Medium brown silty peat
163-180	Brown/grey very organic silt
180+	Solid

BC/6/3 (NX 46373 62143)
10.98m O.D.

0-200	Black/dark brown well humified peat
200-213	Brown/grey very organic silty clay
213-223	Wood
223-231	Dark brown well humified peat with wood
231-258	Brown/grey very organic silty clay
258-289	Brown well humified woody peat
289-295	Brown/grey silty peat
295-304	Brown well humified peat
304-311	Brown/grey organic silty clay
311-319	Brown silty peat
319-345	Brown/grey banded organic silty clay with wood
345-365	Brown well humified sloppy peat (contamination?)
365-375	Brown/grey organic silt
375-391	Brown well humified sloppy peat (contamination?)
391-460	Dark grey organic silt
460-505	Dark brown well humified peat with wood
505-570	Brown/grey banded to blue/grey organic silty clay
570	Solid

BC/6/4 (NX 46363 62139)
10.64m O.D.

0-204	Black/dark brown well humified peat with fibres and wood
204-227	Brown/grey banded silty peat with wood
227-232	Brown well humified peat
232-267	Grey organic silty clay
267-279	Wood
279-300	Brown well humified silty peat
300-414	Grey to brown/grey banded organic silty clay with Phragmites
414-549	Blue/grey silty clay with Phragmites
549-563	Brown well humified wood peat
563-573	Brown/grey very organic woody silt
573-579	Blue/grey organic silty clay
579-587	Brown/grey banded peaty silt
587-690	Brown/grey organic silt
690-748	Blue/grey silty clay
748-753	Brown well humified peat with Phragmites
753-800+	Blue/grey silty clay

BC/6/5 (NX 46353 62138)
10.43m O.D.

0-206	Black/dark brown well humified wood peat
206-218	Brown very organic silt
218-230	Blue/grey silty clay with wood
230-255	Wood
255-267	Brown well humified silty peat
267-271	Wood
271-285	Brown/grey very organic silt
285-312	Blue/grey silty clay with organics
312-330	Brown well humified peat
330-412	Brown/grey banded very organic silty clay
412-425	Brown well humified silty peat with wood
425-531	Blue/grey silty clay with wood and Phragmites
531-551	Wood
551-556	Brown well humified silty peat
556-559	Shock blue silty clay
559-569	Dark brown well humified silty peat

569-577	Brown/grey organic silt
577-583	Blue/grey silty clay with <u>Phragmites</u>
583-605	Brown/grey organic silt
605-700	Blue/grey silty clay
700-709	Wood
709-743	Blue/grey silty clay
743-746	Brown silty peat
746-800+	Blue/grey silty clay

BC/6/6 (NX 46333 62133)
10.11m O.D.

0-224	Black/dark brown peat
224-233	Brown/grey organic silt
233-242	Grey/brown banded organic silty clay with wood
242-257	Dark brown well humified fibrous peat
257-300	Grey/brown banded organic silty clay with wood
300-321	Blue/grey silty clay
321-328	Brown organic silt
328-532	Blue/grey silty clay
532-537	Brown/grey organic silty clay
537-550	Brown well humified silty peat with fibres
550-728	Brown/grey banded organic silty clay
728-730	Brown well humified peat
730-800+	Blue/grey silty clay

BC/6/7 (NX 46314 62128)
10.02m O.D.

0-229	Black/dark brown well humified fibrous peat
229-253	Brown very organic silt
253-278	Brown/grey organic silty clay with <u>Phragmites</u>
278-310	Dark brown woody well humified peat
310-316	Grey/brown organic silty banded clay
316-325	Brown silty peat
325-360	Grey/blue grey organic silty clay
360-370	Brown silty peat
370-434	Blue/grey organic silty clay (banded)
434-534	Blue/grey silty clay
534-536	Brown/grey banded organic silt
536-733	Blue/grey silty clay with <u>Phragmites</u>
733-737	Brown/grey organic silty clay
737-800+	Blue/grey silty clay

Additional boreholes were undertaken at the point where a gravel ridge feature dissappeared beneath the ground surface at Blairs Croft. These boreholes follow on from transect six and are thus included here.

BC/6/8 (NX 46293 62023)
9.91m O.D.

0-160	Dark brown well humified peat with occasional wood fragments and fibres
160	Hit solid (gravel)

BC/6/9 (NX 46282 62017)
9.88m O.D.

0-35	Dark brown peat
35	Hit solid (gravel)

BC/6/10 (NX 46273 62010)
9.86m O.D.

0-42	Dark brown well humified peat with occasional fibres
42-78	Light grey silty clay
78-90	Medium/coarse sand with silty clay
90-135	Brown/grey organic silty clay with gravel
135	Hit solid (gravel)

BC/6/11 (NX 46264 62005)
9.99m O.D.

0-102	Dark brown well humified peat with wood fragments
102-120	Grey silty clay
120-155	Grey silty sandy clay and gravel matrix
155	Hit solid (gravel)

BC/6/12 (NX 46254 62001)
10.02m O.D.

0-124	Dark brown well humified peat
124-150	Blue/grey silty clay
150-165	Brown/grey very organic silty clay
165-200+	Sands and gravels (impenetrable)

BC/6/13 (NX 46245 61993)
9.92m O.D.

0-59	Dark brown well humified peat
59-245	Blue/grey silty clay with organic fleks
245+	Sandy gravel and silty clay matrix (impenetrable)

BC/6/14 (NX 46237 61986)
9.97m O.D.

0-40	Dark brown well humified peat with occasional wood fragments
40-255	Blue/grey silty clay
255+	Hit solid (gravel)

BC/6/15 (NX 46228 61982)
10.01m O.D.

0-72	Dark brown well humified peat with wood fragments
72-275	Blue/grey silty clay with wood fragments
275	Hit solid (gravel)

BC/6/16 (NX 46218 61975)
10.01m O.D.

0-45	Dark brown well humified peat
45-70	Brown/grey very organic silty clay
70-300	Blue/grey silty clay
300+	Small gravel in blue/grey silty clay (impenetrable)

BC/6/17 (NX 46210 61970)
9.96m O.D.

0-64	Dark brown well humified peat
64-400+	Blue/grey silty clay

BC/6/18 (NX 46276 62023)
10.04m O.D.

0-80	Dark brown well humified peat with fibres
80	Hit solid (gravel)

BC/6/19 (NX 46270 62033)
10.35m O.D.

0-100	Dark brown well humified peat with fibres and wood fragments
100	Hit solid (gravel)

BC/6/20 (NX 46266 62042)
10.20m O.D.

0-75	Dark brown well humified peat
75-100+	Blue/grey silty clay and gravel (impenetrable)

BC/6/21 (NX 46260 62052)
10.29m O.D.

0-75	Dark brown well humified peat with wood fragments
75	Hit solid (gravel)

BC/6/22 (NX 46255 62060)
10.22m O.D.

0-47	Dark brown well humified peat
47-55	Brown/grey organic silty clay
55-70+	Grey sand/silt/clay/gravel matrix (impenetrable)

BC/6/23 (NX 46250 62070)
10.16m O.D.

0-60	Dark brown well humified peat
60-70+	Grey sand/silt/clay/gravel matrix (impenetrable)

BC/6/24 (NX 46240 62050)
10.31m O.D.

0-148	Dark brown well humified peat with wood fragments
148-176	Grey silty clay with wood fragments
176-193	Grey coarse sand
193-200	Grey silty sandy clay
200+	Hit solid (gravel)

BC/6/25 (NX 46219 62120)
10.51m O.D.

0-47	Dark brown well humified peat
47-275	Blue/grey silty clay with occasional organic fleks
275	Hit solid (gravel)

BC/7/1 (NX 46380 61945)
11.22m O.D.

0-82	Black well humified peaty top soil
82-120	Brown/grey gritty silt
120	Solid

BC/7/2 (NX 46370 61940)
10.76m O.D.

0-52	Black/dark brown well humified peat
52-87	Grey organic silty clay with wood
87-100	Black well humified peat
100-113	Grey organic silt
113-125	Brown/grey very organic silt
125-141	Grey organic silt
141-170	Brown/grey very organic silt
170	Solid

BC/7/3 (NX 46362 61937)
10.40m O.D.

0-36	Dark brown well humified fibrous peat
36-46	Brown/grey organic silt
46-69	Blue/grey organic silty clay
69-89	Brown/grey organic silt
89-104	Blue/grey organic silty clay
104-113	Brown/grey very organic silt
113-133	Brown well humified silty peat
133-140	Grey organic silty clay
140-172	Brown very organic banded silty peat
172-182	Brown/grey organic silt
182-200	Brown very organic silty peat
200-241	Blue/grey organic silty clay
241-250	Dark grey very coarse sand/gravel/silt matrix
250	Solid

BC/7/4 (NX 46351 61935)

0-123	Black/dark brown well humified fibrous peat
123-136	Brown/grey very organic silty clay
136-211	Blue/grey organic silty clay with Phragmites
211-229	Brown very organic silty peat
229-253	Grey very organic clay
253-262	Brown very organic silty clay
262-305	Grey banded organic silty clay
305-395	Blue/grey silty clay
395-407	Brown well humified peat with wood
407-427	Blue/grey silty clay with wood
427-440	Brown very organic peaty silt with wood
440-473	Brown/grey banded very organic silt
473-482	Brown very organic peaty silt
482-500	Brown/grey organic silt
500-615	Blue/grey silty clay
615	Solid

BC/7/5 (NX 46343 61930)
9.89m O.D.

0-122	Dark brown well humified peat
122-132	Brown/grey organic silt
132-193	Blue/grey silty clay with organics
193-200	Brown silty peat
200-225	Grey organic clay
225-241	Brown/grey very organic silt
241-246	Brown well humified peat
246-266	Brown/grey banded organic clay
266-274	Brown well humified peat
274-310	Brown/grey banded organic clay
310-439	Blue/grey silty clay
439-457	Brown well humified wood peat
457-490	Brown/blue grey banded very organic silty clay
490-800+	Blue/grey silty clay

BC/7/6 (NX 46337 61929)
9.84m O.D.

0-105	Dark brown/black well humified peat
105-169	Blue/grey silty clay with organics (wood at 123-148)
169-212	Brown/grey silty peat
212-245	Grey/brown banded organic silty clay
245-252	Brown well humified silty peat
252-310	Grey banded organic silty clay
310-442	Blue/grey silty clay with *Phragmites*
442-454	Dark brown well humified peat with fibres
454-500+	Brown/grey banded organic silty clay

BC/7/7 (NX 46333 61928)
9.77m O.D.

0-155	Dark brown/black well humified peat
155	Solid

BC/7/8 (NX 46307 61919)
9.78m O.D.

0-125	Dark brown well humified peat
125-155	Dark grey sand/gravel/silt matrix
155	Solid

BC/7/9 (NX 46270 61905)
10.22m O.D.

0-155	Dark brown well humified peat
155-300	Blue/grey very organic silt
300-318	Brown/grey very organic silt
318-364	Blue/grey organic silty clay
364-371	Brown/grey very organic silt
371-500	Blue/grey silty clay
500-550	Light brown/grey organic silty clay
550+	Blue/grey silty clay

BC/8/1 (NX 46380 61837)
m O.D.

0-30	Black peaty top soil with rootlets
30-35	Red/brown fibrous peat
35-36	Becoming silty
36-41	Grey/brown silty clay (some rootlets)
41-102	Blue/grey silty clay (organics and wood fragments at 42-44, 50-60 and 65-70)
102-140	Brown silty woody peat
140-151	Grey/brown organic silty clay
151-215	Blue/grey silty clay (wood fragments)
215	Solid

BC/8/2 (NX 46367 61828)
m O.D.

0-31	Dark brown peaty top soil
31-270	Grey clay
270	Stopped by gravel

BC/8/3 (NX 46353 61822)

m O.D.	
0-28	Black well humified peaty top soil
28-80	Blue/grey silty clay with orange mottling (sand layers at 39-42 and 61-64)
80-164	Blue/grey silty clay (some organics)
164-214	Brown/grey clay
214-221	Brown peaty clay
221-422	Brown grey clay
422-427	Brown/grey peaty clay
427-466	Very organic clay
466-901	Blue/grey silty clay
901-908+	Dark brown well humified compact peat

BC/8/4 (near to BC/8/3)

m O.D.	
0-79	Disturbed top soil
70-84	Dark blue/grey silty sand
84-130	Blue/grey silty clay (sand lenses)
130+	Solid (stones)

BC/8/5 (near to BC/8/3)

m O.D.	
0-16	Black well humified peaty top soil
16-100	Brown/grey silty clay
100-123	Blue/grey silty clay with sandy inclusions
123	Solid (stone)

BC/8/6 (near to BC/8/3)

m O.D.	
0-15	Black peaty top soil
15-155	Brown/grey silty clay
155	Solid (stone)

Barholm Mains (BM)

BM 1 (NX 4693 5960)

No altitude taken	
0-42	Grey organic silty sandy clay (mottled)
42-54	Very organic silty sandy clay with small clasts
54-190	Steel grey silty sand
190	Too tough to penetrate

BM 2 (NX 4683 5964)

No altitude taken	
0-285	Mottled brown/blue silty sandy clay
285-298	Sand
298-435	Grey silty clay
435-475	Pinkish silty clay
475	Solid (stone?)

Castle Clary (CY)

CY 1 (NX 4750 5797)
8.20m O.D.

0-30	Brown/grey silty peat
30-360	Grey silty clay
360-412	Medium sand with shells
412-1210+	Grey silty clay with occasional shells (very dark grey after 730)

CY 2 (NX 4755 5793)
8.61m O.D.

0-32	Black peaty top soil
32-131	Grey silty clay with Phragmites
131-222	Brown/grey silty clay
222-384	Medium grey sand
384	Solid

Carslae Cottage (CC)

CC 1 (NX 4258 5823)
9.01m O.D.

0-10	Brown/grey organic silty clay (top soil)
10-527	Grey silty clay
527	Solid

CC 2 (NX 4264 5825)
8.77m O.D.

0-121	Light brown grey clay
121-135	Organic brown grey clay
135-710	Blue/grey silty clay (occasional black mottling & sandy laminae)
710-717	Dark grey gritty sand
717-1110	Light grey clay with black flecks
1110	Did not proceed (equipment limitations)

Borrow Moss (BM)

BM 1 (NX 4272 4784)
8.95m O.D.

0-18	Top soil
18-57+	Blue/grey silty clay

BM 2 (NX 4284 5791)
11.53m O.D.

0-15	Very dark brown/black dry Sphagnum peat
15-57	Dark brown Sphagnum peat with fibres
57-285	Very dark brown Sphagnum peat with wood
285-306	Brown/grey silty peat with wood
306-370+	Blue/grey silty clay

BM 3 (NX 4305 5803)
12.58m O.D.

0-11	Very dark brown soggy Sphagnum peat
11-53	Orange/brown Sphagnum peat with fibres
53-380	As above but wetter
380-407	Brown/grey well humified silty peat (transitional) with wood
407-500+	Blue/grey silty clay (wood at top)

BM 4 (NX 4328 5814)
11.94m O.D.

0-10	Very dark Sphagnum peat with fibres and Eriophorum
10-336	Orange/brown Sphagnum fibrous peat
336-348	Dark brown/black well humified peat with wood
348-400+	Blue/grey silty clay

BM 5 (NX 4347 5810)
11.86m O.D.

0-100	No recovery - too sloppy (Sphagnum peat)
100-314	Orange/brown to red/brown Sphagnum peat with fibres
314-340	Brown well humified woody peat with fibres
340-400+	Blue/grey silty clay with wood at top

BM 6 (NX 4336 5804)
12.05m O.D.

0-329	Orange/brown Sphagnum peat with fibres
329-360	Dark brown well humified peat with wood
360-369	Brown/grey peaty clay (transitional)
369-400+	Blue/grey silty clay

BM 7 (NX 4323 5796)
12.44m O.D.

0-15	Very dark brown fibrous peat
15-363	Orange/brown to red/brown fibrous Sphagnum peat with Eriophorum
363-381	Very dark brown/black well humified peat with wood
381-395	Brown/grey peaty clay (transitional)
395-400+	Blue/grey silty clay

BM 8 (NX 4312 5789)
12.47m O.D.

0-12	Very dark brown/black well humified Sphagnum peat with Calluna rootlets
12-24	Brown Sphagnum peat with fibres
24-346	Orange/brown to red/brown fibrous Sphagnum peat
346-400	Dark brown/black well humified peat with wood
400-430+	Blue/grey silty clay

BM 9 (NX 4301 5782)
10.98m O.D.

0-43	Dark brown peaty fibrous top soil
43-173	Brown Sphagnum fibrous peat
173-231	Black well humified peat with Eriophorum
231-260	Black well humified woody peat - some clay toward base
260-300+	Blue/grey silty clay

BM 10 (NX 4318 5778)
11.64m O.D.

0-10	Dark brown/black well humified fibrous peat
10-203	Brown to orange/brown Sphagnum peat with fibres
203-300	Dark brown well humified Sphagnum peat with Eriophorum
300-315	Brown/grey peaty clay with wood (transitional)
315-380+	Blue/grey silty clay

BM 11 (NX 4337 5789)
11.94m O.D.

0-5	Black well humified peat
5-326	Orange/brown to red/brown Sphagnum peat with Eriophorum
326-356	Dark brown well humified Sphagnum peat with Eriophorum
356-380	Grey/brown peaty clay with wood and charcoal? (transitional)
380-400+	Blue/grey silty clay

Carsegowan Moss (CGM)

CGM 1 (NX 42195 58863)
13.09m O.D.

0-31	Black peaty top soil with wood (Betula) fragments
31-59	Dark brown fibrous well humified Sphagnum peat
59-87	Orange/brown fibrous Sphagnum peat with Phragmites
87-134	As above but red/brown and with wood
134-240	Dark brown woody fibrous Sphagnum peat
240-267	Dark brown compact woody peat with some clay inclusions
267-302	As above but increasing gravel content toward the base
302-305	Gritty organic silt
305	Solid

CGM 2a (NX 42205 58865)
13.25m O.D.

0-36	Dark brown fibrous peat
36-140	Orange/brown fibrous Sphagnum peat with Eriophorum and wood (Betula)
140-166	Dark brown Sphagnum peat with Betula fragments
166-171	As above but darker
171-262	Dark brown wood peat with Phragmites
262-362	Dark brown Phragmites peat
362-381	Brown/grey peaty clay with wood
381-404	Dark grey clay
404-435	Dark grey clay with wood and stones
435	Impenetrable

CGM 2b (NX 42215 58868)
m O.D.

0-110	Dark brown peaty top soil
110-257	Dark brown sloppy Eriophorum peat
257-338	Dark red/brwon well humified Sphagnum peat
338-345	Wood
345-355	Brown/grey organic clay with wood
355-429	Blue/grey silty clay
429-453	Blue/grey silty clay with abundant shells
453-480	Blue/grey silty clay with shell fragments
480	Solid

CGM 2c (NX 42230 58870)
m O.D.

0-10	Top soil
10-41	Dark brown fibrous Sphagnum peat
41-208	Orange/brown Sphagnum peat with wood and Eriophorum
208-279	Very dark brown Sphagnum peat with wood and Phragmites
279-323	Brown well humified Sphagnum peat
323-328	Clay band
328-333	Very dark brown well humified Sphagnum peat with Phragmites
333-436	Blue/grey silty clay
436-458	Blue/grey silty clay with shells

458-550	Blue/grey silty clay
550-555	Blue/grey silty clay with shells
555-600+	Blue/grey silty clay

CGM 3 (NX 4234 5888)
12.81m O.D.

0-13	Dark brown well humified Sphagnum fibrous peat
13-35	Orange/brown Sphagnum fibrous peat
35-100	Orange/brown sloppy Sphagnum peat
100-146	Red/brown Sphagnum peat with occasional Calluna rootlet
146-200	Orange/brown sloppy Sphagnum peat
200-264	Red/brown humified Sphagnum peat
264-300	Dark brown well humified peat
300-303	Wood (Alnus?)
303-346	Dark brown well humified Sphagnum peat
346-355	Brown/grey peaty clay with some wood fragments
355-469	Blue/grey silty clay
469-493	Blue/grey silty clay with black mottling
493-500+	Blue/grey silty clay

CGM 4 (NX 4239 5890)
13.05m O.D.

0-16	Dark brown well humified Sphagnum peat with Calluna rootlets
16-100	Orange/brown Sphagnum peat
100-313	Orange/brown more humified Sphagnum peat
313-322	Dark brown fibrous Sphagnum peat
322-334	Dark brown well humified fibrous peat
334-382	Dark brown well humified Sphagnum peat
382-410	Brown/grey clay
410-461	Dark blue/grey silty clay
461-494	Blue/grey silty clay
494-552+	Dark grey silty clay with black mottling (very dry)

CGM 5 (NX 4249 5892)
12.99m O.D.

0-200	Sloppy peat (not recovered)
200-313	Dark brown Sphagnum peat
313-340	Very dark brown Eriophorum and Sphagnum peat
340-404	Very dark brown well humified peat
404-500+	Blue/grey silty clay

CGM 6 (NX 4265 5894)
12.90m O.D.

0-215	Sloppy peat (not recovered)
215-304	Dark brown Eriophorum and Sphagnum peat
304-359	Black well humified peat with Phragmites
359-363	Wood (Betula)
363-378	Brown/grey peat with some clay
378-400+	Blue/grey silty clay

CGM 7 (NX 4285 5896)
12.37m O.D.

0-12	Black humified Sphagnum peat
12-206	Orange/brown Sphagnum peat
206-227	Dark brown Sphagnum peat with Eriophorum
227-327	Dark brown well humified peat with wood
327-356	Brown peat with wood and Phragmites
356-400+	Blue/grey silty clay

CGM 8 (NX 4302 5898)
11.84m O.D.

0-15	Very dark brown Sphagnum peat
15-248	Orange/brown Sphagnum peat
248-287	Black well humified peat with wood and Phragmites
287-300+	Blue/grey silty clay

CGM 9 (NX 4303 5895)
12.24m O.D.

0-135	Dark brown Sphagnum peat
135-239	Orange/brown Sphagnum peat with Eriophorum
239-332	Dark brown well humified peat
332-342	Dark brown well humified woody peat
342-400+	Blue/grey silty clay

CGM 10 (NX 4305 5886)
12.04m O.D.

0-15	Dark brown/black well humified peat
15-100	Orange/brown to brown fibrous Sphagnum and Eriophorum peat
100-200	Dark brown sloppy peat
200-235	Red brown soggy Eriophorum and Sphagnum peat
235-317	Dark brown well humified peat with Eriophorum, Sphagnum, wood and Calluna rootlets
317-332	Brown/grey peaty clay with Phragmites
332-400+	Blue/grey silty clay

CGM 11 (NX 4287 5884)
11.94m O.D.

0-15	Very dark brown fibrous peat
15-100	Light brown fibrous Sphagnum peat
100-132	Brown Sphagnum sloppy peat
132-144	Orange/brown Sphagnum peat
144-272	Brown sloppy Sphagnum peat
272-300	Dark brown Sphagnum and Eriophorum peat with wood
300-400	Dark brown well humified peat with wood and Phragmites
400-500+	Blue/grey silty clay

CGM 12 (NX 4267 5882)
12.78m O.D.

0-100	Sloppy Sphagnum peat (not recovered)
100-300	Orange/brown sloppy Sphagnum peat
300-374	Dark brown well humified peat
374-400	Dark brown well humified peat with some clay and wood
400-500+	Blue/grey silty clay with wood near contact

CGM 13 (NX 4255 5879)
12.94m O.D.

0-100	Sloppy Sphagnum peat (not recovered)
100-364	Dark brown Sphagnum peat
364-400	Brown/grey well humified peat with clay and twigs
400-500+	Blue/grey silty clay

CGM 14 (NX 4242 5878)
12.89m O.D.

0-100	Sloppy <u>Sphagnum</u> peat (not recovered)
100-241	Dark orange/brown <u>Sphagnum</u> peat
241-261	Light orange brown <u>Sphagnum</u> peat
261-343	Dark brown well humified peat
343-372	Brown/grey peaty clay
372-400+	Blue/grey silty clay

CGM 15 (NX 4246 5867)
12.69m O.D.

0-30	Brown fibrous compact peat
30-261	Orange/brown <u>Sphagnum</u> peat and twigs
261-337	Very dark brown <u>Spagnum</u> peat and twigs
337-343	Light grey silty clay
343-347	Brown/grey clay peat with wood
347-400+	Blue/grey silty clay

CGM 16 (NX 4265 5868)
12.32m O.D.

0-16	Very dark brown <u>Sphagnum</u> peat
16-150	Orange/brown <u>Sphagnum</u> fibrous peat
150-211	Red/brown <u>Sphagnum</u> peat
211-318	Very dark brown well humified <u>Sphagnum</u> peat with wood and <u>Phragmites</u>
318-337	Brown well humified peat with <u>Phragmites</u>, wood and clay
337-400+	Blue/grey silty clay

CGM 17 (NX 4281 5869)
12.70m O.D.

0-100	Dark brown fibrous <u>Sphagnum</u> peat
100-308	Orange/brown to red/brown <u>Sphagnum</u> peat with <u>Eriophorum</u>
308-393	Very dark brown well humified <u>Sphagnum</u> peat with <u>Eriophorum</u>
393-450+	Blue/grey silty clay

CGM 18 (NX 4297 5872)

0-312	Orange/brown to red/brown sloppy <u>Sphagnum</u> peat
312-393	Very dark brown well humified peat with wood
393-400+	Blue/grey silty clay

Carsegowan Farm basin (CGM/B)

CGM/B/1 (NX 41975 58960)
12.66m O.D.

0-30	Light brown fibrous peaty top soil
30	Solid (bedrock?)

CGM/B/2 (NX 41993 58965)
12.46m O.D.

0-33	Top soil
33-69	Black well humified peat
69-117	Medium brown fibrous peat (wood at 72; hazel nut at 85)
117-138	Dark brown to grey wet peat
138-176	Medium grey silty sand
176-200	Medium grey silty sand (increasing silt/clay content)
200-281	Blue/grey sandy silty clay
281	Solid

CGM/B/3 (NX 42011 58968)

12.33m O.D.

0-40	Top soil
40-90	Black well humified peat with fibres and wood
90-116	Dark brown well humified peat
116-129	Black well humified peat
129-159	Light brown fibrous peat with Phragmites
159-177	Black dense peat with fibres
177-181	Brown/grey organic silt (transitional)
181-195	Grey sandy silt
195-200	Grey sandy silt with increasing sand content
200	Solid

CGM/B/4 (NX 42032 58972)

12.49m O.D.

0-13	Peaty top soil
13-105	Dark brown/black well humified fibrous peat
105-161	Dark brown fibrous peat with wood and Eriophorum
161-213	Orange/brown fibrous peat
213-228	Blue/grey silty clay
228-240	Blue/grey sandy silty clay
240-256	Blue/grey silty clay
256-259	Grey (green tinge) silt
259-290	Blue/grey silty clay
290	Solid

CGM/B/5 (NX 42050 58975)

0-23	Top soil
23-55	Dark brown/black well humified peat (wood at 50)
55-175	Brown/black well humified fibrous peat
175-212	Blue/grey silty clay (stone at 192)
212	Solid

CGM/B/6 (NX 42070 58980)

11.78m O.D.

0-55	Peaty top soil
55-138	Black well humified peat with wood at 70-78
138-164	Blue/grey clay
164-174	Blue/grey silty clay
174-176	Light brown well humified crumbly peat
176-190	Grey silty clay
190-200	Blue/grey silty clay
200	Solid

CGM/B/7 (NX 42081 58983)

11.51m O.D.

0-26	Top soil
26-90	Dark brown/black well humified peat with wood at 72
90-106	Dark brown well humified peat
106-168	Grey silty clay
168-172	Brown well humified crumbly peat
172-174	Grey silty clay
174-179	Brown well humified crumbly peat
179-194	Grey silty sandy clay
194-288	Blue/grey silty clay
288	Solid

CGM/B/8a (NX 42040 58933)
12.38m O.D.

0-35	Top soil
35-63	Black well humified peat with wood
63-100	Orange/brown fibrous peat
100-158	Dark brown well humified peat with fibres
158-200	Grey clay
200	Solid

CGM/B/8b (NX 42043 58923)
12.34m O.D.

0-36	Top soil
36-131	Dark brown/black well humified peat
131-153	Grey silty clay
153-180	Dark grey silty clay
180	Solid

CGM/B/9 (NX 42045 58913)
12.24m O.D.

0-57	Dark brown peaty top soil
57-95	Dark brown/black well humified peat
95	Solid

CGM/B/10 (NX 42049 58893)
12.30m O.D.

0-46	Top soil
46-64	Dark brown well humified peat
64	Solid

CGM/B/11 (NX 42026 59007)
12.48m O.D.

0-67	Top soil
67	Solid

CGM/B/12 (NX 42007 59002)
12.41m O.D.

0-40	Top soil
40-90	Black well humified peat
90-100	Wood
100	Solid

CGM/B/13 (NX 41985 58994)
12.48m O.D.

0-40	Top soil
40-79	Black well humified peat with wood
79-108	Light blue grey silty sandy clay
108-123	Blue/grey silty clay with wood
123	Solid

CGM/B/14 (NX 41982 59003)
12.80m O.D.

0-47	Top soil
47	Solid

CGM/B/15 (NX 42028 58992)
12.35m O.D.

0-20	Top soil
20-45	Dark brown well humified peat
45-100	Orange/brown fibrous peat
100-136	Dark brown well humified peat with wood
136-150	Orange/brown fibrous peat
150-180	Dark brown well humified fibrous peat
180-200	Grey clay
200-228	Grey silty clay
228-250	Blue/grey silty clay
250	Solid

CGM/B/16 (NX 42002 58925)
12.24m O.D.

0-62	Top soil
62	Solid

CGM/B/17 (NX 41997 58944)
12.53m O.D.

0-46	Top soil
46-61	Black well humified peat
61	Solid

Moss of Cree (MOC)

MOC 1 (NX 4327 5987)
11.22m O.D.

0-65	Dark brown fibrous Sphagnum peat
65-163	Orange/brown Sphagnum fibrous peat
163-189	Brown/grey well humified peat with Sphagnum
189-225	Brown well humified fibrous peat with Eriophorum, wood and Phragmites
225-300+	Blue/grey silty clay

MOC 2 (NX 4335 5991)
12.65m O.D.

0-15	Dark brown Sphagnum peat with fibres
15-324	Orange/brown Sphagnum peat with fibres and Eriophorum after 300
324-344	Black well humified Sphagnum peat
344-367	Dark brown well humified sloppy Sphagnum peat with wood fragments
367-400+	Blue/grey silty clay

MOC 3 (NX 4347 5995)
12.47m O.D.

0-100	None recovered (peat)
100-248	Orange/brown to red sloppy Sphagnum peat with Eriophorum
248-307	Dark brown well humified Sphagnum peat with Calluna rootlets
307-351	Orange/brown Sphagnum peat
351-400+	Blue/grey silty clay (sharp contact)

MOC 4 (NX 4361 6000)
12.24m O.D.

0-127	Dark brown fibrous Sphagnum peat
127-200	Orange/brown fibrous Sphagnum peat with Eriophorum
200-311	Orange/brown to dark brown Sphagnum well humified peat with Eriophorum
311-328	Blue/grey silty clay
328-338	Dark brown well humified peat with some clay
338-400+	Blue/grey silty clay

MOC 5 (NX 4376 6005)
13.08m O.D.

0-8	Black well humified Sphagnum peat
8-239	Red/brown fibrous Sphagnum peat
239-327	Dark brown well humified peat with fibres, wood and Eriophorum
327-400+	Blue/grey silty clay

MOC 6 (NX 4387 6009)
12.70m O.D.

0-110	Orange/brown to dark brown Sphagnum peat with fibres
110-262	Orange/brown Sphagnum fibrous peat with Eriophorum
262-286	Dark brown sloppy well humified peat
286-293	Brown/grey peaty clay
293-300+	Blue/grey silty clay

MOC 7 (NX 4308 6022)
12.35m O.D.

0-50	Brown compact Sphagnum peat with fibres
50-210	Orange/brown Sphagnum fibrous peat
210-330	Dark brown well humified peat
330-340	Brown/grey peaty clay
340-400+	Blue/grey silty clay

MOC 8 (NX 4297 6047)
11.42m O.D.

0-35	Top soil
35-112	Brown Sphagnum fibrous compact peat
112-225	Orange/brown to brown Sphagnum well humified peat with wood and Eriophorum
225-240	Brown/grey peaty clay
240-300+	Blue/grey silty clay

MOC 9 (NX 4342 5953)
10.99m O.D.

0-10	Top soil
10-88	Dark brown Sphagnum fibrous peat
88-102	Dark brown well humified peat
102-220	Orange/brown to dark brown well humified fibrous compact Sphagnum peat
220-248	Brown well humified compact peat with wood fragments
248-300+	Blue/grey silty clay

MOC 10 (NX 4395 6010)
10.30m O.D.

0-39	Light brown compact Sphagnum fibrous peat
39-136	Dark brown compact well humified peat with some fibres
136-142	Brown/grey peaty clay
142-200+	Blue/grey silty clay

MOC 11 (NX 4406 6013)
9.19m O.D.

0-33	Brown compact fibrous Sphagnum peat
33-52	Brown/grey peaty clay
52-100+	Blue/grey silty clay

MOC 12 (NX 4417 6008)
9.04m O.D.

0-12	Brown compact peat with roots (top soil)
12-37	Dark brown well humified Sphagnum peat
37-100+	Blue/grey silty clay

MOC 13 (NX 4432 6006)
10.72m O.D.

0-10	Peaty top soil
10-76	Dark brown to black Sphagnum peat with fibres
76-122	Orange/brown fibrous Sphagnum peat with wood fragments
122-191	Dark brown/black well humified peat with wood from 160-191
191-200+	Blue/grey silty clay

MOC 14 (NX 4447 6007)
11.10m O.D.

0-230	Dark brown well humified peat with fibres and Eriophorum from 190-230
230-248	Dark brown/black well humified fibrous peat
248-257	Dark brown sloppy wood peat with wood
257-278	Brown/grey peaty clay with wood
278-300+	Blue/grey silty clay

MOC 15 (NX 4462 6003)
10.26m O.D.

0-74	Black dry compact peat
74-106	Black compact well humified peat
106-184	Dark brown well humified peat with wood after 160 and Eriophorum
184-200+	Blue/grey silty clay

MOC 16 (NX 4474 6063)
10.76m O.D.

0-255	Brown to orange/brown Sphagnum peat with fibres and Eriophorum
255-259	Brown/grey organic clay
259-300+	Blue/grey silty clay with Phragmites

Moss of Cree (Baltersan Farm)

MOC 17 (NX 4320 6211)
11.02m O.D.

0-68	Dark brown/black well humified Sphagnum peat with fibres
68-90	Orange/brown Sphagnum peat with fibres
90-107	Black compact peat with fibres
107-179	Brown well humified peat with Phragmites near base
179-195	Light brown organic clay
195-208	Brown/grey peaty clay
208-230	Dark brown well humified peat with Phragmites
230-260	Brown/grey organic clay
260-300+	Blue/grey silty clay

MOC 18 (NX 4314 6205)
12.26m O.D.

0-35	Black compact well humified peat with fibres
35-200	Brown to orange/brown Sphagnum peat with fibres
200-240	Dark brown well humified Sphagnum peat with fibres
240-262	Black well humified peat with wood
262-300	Dark brown well humified Sphagnum peat with fibres
300-348	Brown/grey peaty clay with Phragmites
348-400+	Blue/grey silty clay with some organics

MOC 19 (NX 4302 6195)
13.11m O.D.

0-10	Fibrous peaty top soil with roots
10-233	Brown fibrous Sphagnum peat with Eriophorum from 200
233-280	Dark brown well humified peat with wood from 260-280
280-284	Brown/grey peaty clay
284-290	Blue/grey silty clay
290-297	Brown/grey organic clay
297-300+	Blue/grey silty clay

MOC 20 (NX 4295 6189)
12.94m O.D.

0-100	Brown Sphagnum peat with fibres and roots
100-236	Orange/brown Sphagnum peat with Eriophorum
236-310	Dark brown well humified peat with wood
310-358	Dark brown well humified peat
358-368	Blue/grey silty clay
368-376	Brown/grey peaty clay
376-402	Dark brown sloppy Sphagnum peat with wood
402-420+	Blue/grey silty clay

MOC 21 (NX 4297 6168)
12.72m O.D.

0-28	Dark brown compact well humified fibrous peat
28-328	Orange/brown to brown Sphagnum peat with fibres, wood and Phragmites
328-343	Brown/grey organic clay
343-365	Brown peaty clay
365-400+	Blue/grey silty clay

MOC 22 (NX 4301 6154)
11.87m O.D.

0-216	Dark brown fibrous Sphagnum compact peat
216-235	Dark brown well humified peat with wood
235-260	Blue/grey silty clay
260-272	Brown/grey organic clay
272-300+	Blue/grey silty clay

MOC A1 (NX 4295 6167)
12.62m O.D.

0-349	Brown/red brown Sphagnum peat
349-355	Brown/grey organic silty clay
355-365	Grey organic silty clay
365-800	Blue/grey silty clay
800-821	Grey/brown organic silt
821-1310+	Blue/grey silty clay

MOC A2 (NX 4293 6147)
No level taken

0-244	Brown Sphagnum peat
244-255	Grey/brown organic silt
255-258	Brown peat
258-300+	Grey/brown organic silt to blue/grey silty clay

MOC A3 (NX 4296 6176)
12.86m O.D.

0-370	Red/brown Sphagnum peat
370-380	Brown/grey organic silty clay
380-395	Dark brown well humified peat
395-500+	Blue/grey silty clay

Carse of Clary (COC)

COC 1 (NX 42650 60225)
9.25m O.D.

0-20	Light brown/grey silty organic clay
20-150	Light grey silty clay
150	Solid (gravel/shingle?)

COC 2 (NX 42713 60248)
9.28m O.D.

0-260	Light grey/blue grey silty clay
260-270	Sand/shingle layer
270-690	Blue/grey silty clay (stone cobble at 306-308)
690-699	Medium brown very organic peaty silt layer
699-715	Blue/grey silty clay with organics
715-740	Dark brown compact peat
740-760+	Sands and gravels

This location (within 5m of original location) was sampled for biostratigraphical analysis at a later date (21/4/1997) and the stratigraphy varied slightly from the original - the details of this are as follows (altitude and grid ref. remains unaltered):

0-270	Light brown/grey to blue/grey silty clay
270-350	Blue/grey silty clay with coarse gravel inclusions with some larger stones and occasional shell fragments
350-440	Blue/grey silty clay
440-668	Blue/grey silty clay with black mottling and occasional organic flek
668-671	Brown/grey silty peat
671-681	Brown/grey organic silty clay
681-685	Brown/grey very organic silt
685-700+	Dark brown well humified compact peat with occasional wood fragment

COC 3 (NX 42680 60235)
9.24m O.D.

0-230	Blue/grey silty clay
230	Solid (gravel/shingle?)

COC 4 (NX 42755 60265)
9.22m O.D.

0-120	Blue/grey silty clay
120-130	Light brown organic clay
130-866	Blue/grey silty clay
866-877	Light brown/grey organic clay
877-900	Blue/grey silty clay
900-904	Brown/grey very organic clay
904-910+	Dark brown compact well humified peat

COC 5 (NX 42725 60253)
9.19m O.D.

0-275	Blue/grey silty clay
275	Solid (shingle)

COC 6 (NX 42723 60252)
9.22m O.D.

0-290	Blue/grey silty clay
290-305+	Shingle layer in silty clay

COC 7 (NX 42718 60250)
9.27m O.D.

0-260	Blue/grey silty clay
260	Solid (shingle)

COC 8 (NX 42699 60240)
9.24m O.D.

0-260	Blue/grey silty clay
260	Solid (shingle)

COC 9 (NX 42783 60275)
9.23m O.D.

0-110	Blue/grey silty clay
110-150	Brown/grey organic silty clay
150-500	Blue/grey silty clay
500	Solid (shingle/stone?)

COC 10 (NX 42805 60283)
9.23m O.D.

0-116	Blue/grey silty clay with brown mottling
116-130	Brown/grey organic silty clay
130-420	Blue/grey silty clay
420-430	Solid (gravel/shingle) - not recovered

COC 11 (NX 42825 60278)
9.29m O.D.

0-86	Mottled blue/grey silty clay
86-94	Brown/grey organic silty clay
94-450	Blue/grey silty clay
450	Solid (shingle/gravel?)

COC 12 (NX 42738 60343)
9.19m O.D.

0-84	Mottled blue/grey silty clay
84-130	Brown/grey organic silty clay
130-346	Blue/grey silty clay
346-351	Sandy shell debris layer
351-1050+	Blue/grey silty clay (lost gouge but could go deeper)

Baltersan Farm (BAL)

BAL/1 (NX)
9.82m O.D.

0-30	Disturbed brown/grey silty clay
30-180	Blue/grey silty clay
180	Hit solid

BAL/2 (NX)
9.74m O.D.

0-30	Disturbed brown/grey silty clay
30-175	Blue/grey silty clay with shell fragments
175	Hit solid

BAL/3 (NX)
9.80m O.D.

0-20	Disturbed brown/grey silty clay
20-212	Light blue/grey silty clay
212-220	Brown very organic silt
220-228	Light blue/grey silty clay
228-237	Brown silty peat
237+	Green grey gravel

BAL/4 (NX)
9.11m O.D.

0-20	Disturbed brown/grey silty clay
20-63	Blue/grey silty clay
63-100	Brown well humified peat
100-115	Brown/grey very organic silt
115-243	Blue/grey silty clay with organics
243-290	Dark brown well humified peat with wood
290-315	Penetrated gravel and then stopped on solid but none recovered

BAL/5 (NX)
8.72m O.D.

0-27	Disturbed brown/grey silty clay
27-65	Dark brown well humified peat
65-131	Brown/grey to blue/grey organic silty clay
131-141	Brown/grey very organic silty clay with fibres
141-228	Blue/grey organic silty clay
228-285	Dark brown well humified peat with occasional wood fragment
285	Hit solid

BAL/6 (NX)
8.73m O.D.

0-30	Disturbed brown/grey silty clay
30-45	Dark brown well humified peat
45-86	Brown/grey to blue/grey organic silty clay
86-96	Brown very organic silt
96-113	Blue/grey silty clay
113-123	Brown very organic silt
123-211	Blue/grey silty clay
211-260	Dark brown well humified peat with occasional wood fragments
260-280	Grey silty clay (sloppy) - contamination?
280	Hit solid

BAL/7 (NX)
8.58m O.D.

0-20	Disturbed brown/grey silty clay
20-40	Dark brown well humified peat
40-95	Grey to blue/grey silty clay with organic inclusions
95-215	Brown/grey very organic silt
215-249	Dark brown well humified peat with wood fragments
249-260	Brown/grey organic silty clay
260-264	Dark brown silty peat
264-275	Blue/grey silty clay (contamination?)
275	Hit solid

BAL/8 (NX)
8.64m O.D.

0-56	Disturbed brown/grey silty clay
56-390	Blue/grey silty clay
390-405	Dark brown well humified peat
405-545	Blue/grey silty clay
545-570+	Dark brown well humified peat (too tough to penetrate further)

BAL/9 (NX)
8.38m O.D.

0-33	Brown peaty top soil
33-330	Blue/grey silty clay
330-357	Dark brown peat
357-534	Blue/grey silty clay
534-560+	Dark brown well humified peat (too tough to penetrate further)

BAL/10 (NX)
9.03m O.D.

0-40	Disturbed brown/grey silty clay
40-416	Blue/grey silty clay
416-436	Dark brown well humified peat
436-700+	Blue/grey silty clay

BAL/11 (NX)
9.49m O.D.

0-40	Brown peaty top soil
40-360	Blue/grey silty clay
360-371	Brown/grey silty peat
371-700+	Blue/grey silty clay

References

Adams, T. D., and J. R. Haynes. 1965. Foraminifera in Holocene marsh cycles at Borth, Cardiganshire (Wales). *Palaeontology* 8: 27-38.

Admiraal, W. 1984. The ecology of estuarine sediment-inhabiting diatoms. *Progress in Phycological Research* 3: 269-322.

Anderson, N. J., and P. C. Vos. 1992. Learning from the past: Diatoms as palaeoecological indicators of changes in marine environments. *Netherlands Journal of Aquatic Ecology* 26(1): 19-30.

Andrew, R. 1984. *A practical guide to the British flora.*, 139. Technical Guide, 1. Cambridge: Quaternary Research Association.

Athersuch, J., D. J. Horne, and J. E. Whittaker. 1989. *Marine and Brackish Water Ostracods.*, 359. Synopses of the British Fauna (New Series), eds. D. M. Kermack, and R. S. K. Barnes, E.J. Brill.

Atkinson, T. C., K. R. Briffa, and G. R. Coope. 1987. Seasonal temperatures in Britain during the last 22,000 years, reconstructed using beetle remains. *Nature* 325: 587-93.

Austin, W. E. N., and D. Kroon. 1996. Late glacial sedimentology, foraminifera and stable isotope stratigraphy of the Hebridean Continental Shelf, northwest Scotland. In *Late Quaternary Palaeoceanography of the North Atlantic Margins.* eds. J. T. Andrews, W. E. N. Austin, H. Bergsten, and A. E. Jennings, 187-213. Geological Society Special Publication No. 111.

Austin, W. E. N., and D. McCarroll. 1992. Foraminifera from the Irish Sea glacigenic deposits at Aberdaron, western Lleyn, North Wales: palaeoenvironmental implications. *Journal of Quaternary Science* 7(4): 311-17.

Bailey, E. B., C. T. Clough, W. B. Wright, J. E. Richey, and G. V. Wilson. 1924. *Tertiary and Post-Tertiary Geology of Mull, Loch Aline and Oban.* Edinburgh: HMSO.

Ballantyne, C. K. 1990. The late Quaternary glacial history of the Trotternish escarpment, Isle of Skye, Scotland, and its implications for ice-sheet reconstruction. *Proceedings of the Geologists' Association* 101: 171-86.

Ballantyne, C. K., and C. Harris. 1994. *The Periglaciation of Great Britain.*, 330. Cambridge: Cambridge University Press.

Ballantyne, C. K., and D. McCarroll. 1995. The vertical dimensions of Late Devensian glaciation on the mountains of Harris and southeast Lewis, Outer Hebrides, Scotland. *Journal of Quaternary Science* 10(3): 211-23.

Ballantyne, C. K., D. G. Sutherland, and W. J. Reed. 1987. Introduction. *Wester Ross Field Guide.* eds. C. K. Ballantyne, and D. G. Sutherland, 1-63. Cambridge: Quaternary Research Association.

Barber, K. E. 1976. History of Vegetation. *Methods in Plant Ecology.* 1st ed., ed. S. B. Chapman, 5-83. Oxford: Blackwell Scientific Publications.

Bard, E., B. Hamelin, M. Arnold, L. Montaggioni, G. Cabioch, G. Faure, and F. Rougerie. 1996. Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature* 382: 241-44.

Barden, L. 1968. Primary and secondary consolidation of clay and peat. *Geotechnique* 18: 1-24.

Bate, R. H., and B. A. East. 1972. The structure of the ostracode carapace. *Lethaia* 5: 177-94.

Battarbee, R. W. 1973. A new method for the estimation of absolute microfossil numbers, with reference especially to diatoms. *Limnology and Oceanography* 18(4): 647-53.

———. 1986. Diatom Analysis. *Handbook of Holocene Palaeoecology and Palaeohydrology.* ed. B. E. Berglund, 527-70. John Wiley & Sons Ltd.

Becker, B., B. Kromer, and P. Trinbarn. 1992. A stable-isotope tree ring timescale of the Late Glacial/Holocene boundary. *Nature* 353: 647-49.

Beedham, G. E. 1972. *Identification of the British Molluscs.* Amersham (Buckinghamshire): Hulton Educational Publications.

Benn, D. 1991. Glacial landforms and sediments on Skye. In *The Quaternary of the Isle of Skye.* eds. C. K. Ballantyne, D. Benn, J. J. Lowe, and M. J. C. Walker, 35-67. Cambridge: Quaternary Research Association.

Bennett, K. D. 1984. The post-glacial history of *Pinus sylvestris* in the British Isles. *Quaternary Science Reviews*, **3**, 133-155.

Bennett, K. D. and Birks, H. J. B. 1990. Postglacial history of alder (*Alnus glutinosa* (L.) Gaertn.) in the British Isles. *Journal of Quaternary Science*, **5**, 123-133.

Benson, R. H. 1969. Determination of biogeographic boundaries of Quaternary Arctic marine faunas. In *The Taxonomy, Morphology and Ecology of Recent Ostracoda.* ed. J. W. Neale, 249-50. Edinburgh: Oliver & Boyd.

Benzie, J. A. 1989. The distribution and habitat preference of ostracods (Crustacea: Ostracoda) in a coastal sand-dune lake, Loch of Strathbeg, north-east Scotland. *Freshwater Biology* 22: 309-21.

Berglund, B. E., and M. Ralska-Jasiewiczowa. 1986. Pollen analysis and pollen diagrams. In *Handbook of Holocene Palaeoecology and Palaeohydrology.* ed. B. E. Berglund, 455-84. Chichester: John Wiley.

Beyens, L., and L. Denys. 1982. Problems in diatom analysis of deposits: allochtonous valves and fragmentation. *Geologie En Mijnbouw* 61: 159-62.

Birks, H. H. 1972. Studies in the vegetational history of Scotland II. Two pollen diagrams from the Galloway Hills, Kirkcudbrightshire. *Journal of Ecology*, **60**, 183-217.

Birks, H. H. 1975. Studies in the vegetational history of Scotland IV. Pine stumps in Scottish blanket peats. *Philosophical Transactions of the Royal Society of London, Series B* 270: 181-226.

Birks, H. J. B. 1977. The Flandrian forest history of Scotland: a preliminary synthesis. *British Quaternary Studies - Recent Advances.* ed. F. W. Shotton, 119-35. Oxford: Clarendon Press.

———. 1989. Holocene isochrone maps and patterns of tree-spreading in the British Isles. *Journal of Biogeography* 16: 503-40.

———. 1993. Loch Dungeon. In *Quaternary of Scotland.* eds. J. E. Gordon, and D. G. Sutherland, 604-9. London: Chapman & Hall.

Birks, H. J. B, and H. H. Birks. 1980. *Quaternary Palaeoecology.* London: Edward Arnold.

Bishop, W. W. 1963. Lateglacial deposits near Lockerbie, Dumfriesshire. *Transactions of the Dumfriesshire and Galloway Natural History and Antiquarian Society* 40: 117-32.

Bishop, W. W., and G. R. Coope. 1977. Stratigraphical and faunal evidence for Lateglacial and early Flandrian environments in south-west Scotland. *Studies in the Scottish Lateglacial environment.* eds. J. M. Gray, and J. J. Lowe, 61-88. Oxford: Pergamon Press.

Björck, S., B. Kromer, S. Johnsen, O. Bennike, D. Hammarlund, G. Lemdahl, G. Possnert, T. L. Rasmussen, B. Wohlfarth, C. U. Hammer, and M. Spurk. 1996. Synchronised terrestrial-atmospheric records of the last deglaciation yield new insights into major climatic oscillations. *Science* 274: 1155-60.

Blanchon, P., and J. Shaw. 1995. Reef drowning during the last deglaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse. *Geology* 23(1): 4-8.

Bloom, A. L. 1971. Glacial-eustatic and isostatic controls of sea level since the last glaciation. In *The Late Cenozoic Glacial Ages.* ed. K. K. Turekian, 355-79. New Haven, Conneticut: Yale University Press.

Bonsall, C., D. G. Sutherland, R. Tipping, and J. Cherry. 1989. The Eskmeals Project: late Mesolithic settlement and environment in north-west England. In *The Mesolithic in Europe.* ed. C. Bonsall, 175-205. Edinburgh: John Donald.

Boomer, I., and M. Godwin. 1993. Palaeoenvironmental reconstruction in the Breydon Formation, Holocene of East Anglia. *Journal of Micropalaeontology* 12(1): 35-46.

Boulton, G. S., A. S. Jones, K. M. Clayton, and M. J. Kenning. 1977. A British ice sheet model and patterns of glacial erosion and deposition in Britain. In *British Quaternary Studies - Recent Advances.* ed. F. W. Shotton, 231-46. Oxford: Oxford University Press.

Boulton, G. S., G. D. Smith, A. S. Jones, and J. Newsome. 1985. Glacial geology and glaciology of the last mid-latitude ice sheets. *Journal of Geological Society* 142: 447-74.

Bowen, D. Q. 1978. *Quaternary Geology: A stratigraphic framework for multidisciplinary work.*, 221. Oxford: Pergamon Press Ltd.

Boyd, R., and S. Penland. 1984. Shoreface translation and the Holocene stratigraphic record: examples from Nova Scotia, the Mississippi Delta and eastern Australia. *Marine Geology* 60: 391-412.

Boyd, W. E., and J. H. Dickson. 1986. Patterns in the geographical distribution of the early Flandrian *Corylus* rise in southwest Scotland. *New Phytologist* 102: 615-23.

Bradley, R. S. 1985. *Quaternary Paleoclimatology: Methods of Paleoclimatic Reconstruction.*, 472. London: Chapman & Hall.

Brady, G. S. 1866. On new or imperfectly known species of marine Ostracoda. *Transactions of the Zoological Society of London* 5: 359-93.

Brady, G. S., H. W. Crosskey, and D. Robertson. 1874. *A monograph of the Post-Tertiary Entomostraca of Scotland.* London: Palaeontological Society Monograph.

Brady, G. S., and D. Robertson. 1870. The ostracoda and foraminifera of tidal rivers. *The Annals and Magazine of Natural History* 6, no. 31: 1-32.

Brew, D. S., B. M. Funnell, and A. Kreiser. 1992. Sedimentary environments and Holocene evolution of the lower Blyth estuary, Suffolk (England), and a comparison with other East Anglian coastal sequences. *Proceedings of the Geologists' Association* 103(1): 57-74.

Brockmann, C. 1940. Diatmeen als Leitfossilien in Küstenablagerungen . *Westküste* 2: 150-181.

Brooks, C. L. 1972. Pollen analysis and the Main Buried Beach in the western part of the Forth Valley. *Transactions of the Institute of British Geographers* 55: 161-70.

Brown, A. G. 1988. The palaeoecology of *Alnus* (alder) and the Postglacial history of floodplain vegetation. Pollen percentage and influx data from the West Midlands, United Kingdom. *New Phytologist* 110: 425-36.

Browne, M. A. E., M. Armstrong, I. B. Paterson, and A. M. Aitken. 1981. New evidence for Late Devensian marine limits in east central Scotland. *Quaternary Newsletter* 34: 8-15.

Buzer, J. S. 1981. Diatom analyses of sediments from Lough Ine, Co. Cork, southwest Ireland. *New Phytologist* 89: 511-33.

Caljon, A. 1983. *Brackish-water phytoplankton of the Flemish lowland.*, 272. The Hague: Dr W. Junk Publishers.

Cameron, T. D. J., M. S. Stoker, and D. Long. 1987. The history of Quaternary sedimentation in the U.K. sector of the North Sea. *Journal of the Geological Society* 144: 43-58.

Carter, R. W. G., D. L. Forbes, S. C. Jennings, J. D. Orford, J. Shaw, and R. B. Taylor. 1989. Barrier and lagoon coast evolution under differing relative sea-level regimes: examples from Ireland and Nova Scotia. *Marine Geology* 88: 221-42.

Carter, W. G. 1982. Sea-level changes in Northern Ireland. *Proceedings of the Geologists' Association* 93, no. 1: 7-24.

Caseldine, A. 1990. *Environmental archaeology in Wales*. Department of Archaeology, St David's University College: Lampeter.

Chambers, F. M. and Elliott, L. 1989. Spread and expansion of *Alnus* Mill. in the British Isles: timing, agencies and possible vectors. *Journal of Biogeography*, **16**, 541-550.

Chambers, F. M. and Price, S-M. 1985. Palaeoecology of *Alnus* (alder) early post-glacial rise in a valley mire, northwest Wales. *New Phytologist*, **101**, 333-344.

Chappell, J. 1974. Late Quaternary glacio- and hydro-isostasy on a layered earth. *Quaternary Research* 4: 405-28.

Chappell, J., and H. Polach. 1991. Post-glacial sea-level rise from a coral record at Huon Peninsula, Papua New Guinea. *Nature* 349: 147-49.

Charlesworth, J. K. 1926. The glacial geology of the Southern Uplands of Scotland, west of Annandale and Upper Clydesdale. *Transactions of the Royal Society of Edinburgh* 55: 1-23.

Cherrill, A. J., and R James. 1985. The distribution and habitat of four species of Hydrobiidae in East Anglia. *Journal of Conchology London* 32: 123-33.

Clapham, A. R., T. G. Tutin, and D. M. Moore. 1987. *Flora of the British Isles.* 3rd ed., 688. Cambridge: Cambridge University Press.

Clark, R. L. 1982. Point count estimation of charcoal in pollen preparations and thin sections of sediments. *Pollen Et Spores* 24: 523-35.

Cleve-Euler, A. 1951-1955. Die Diatomeen von Schwede und Finnland. *Kungliga Svenska Vetenskapakademiens, Handlingar* 4(e).

Coles, B. P. L. 1977. *The Holocene Foraminifera and palaeogeography of Central Broadland.* Unpublished PhD Thesis, University of East Anglia.

Coles, B. P. L., and B. M. Funnell. 1981. Holocene palaeoenvironments of Broadland, England. In *Holocene marine sedimentation in the North Sea Basin.* eds. S-D. Nio, R. T. E. Shuttenhelm, and T. C. E. Van Weering, 123-31. Vol. 5. Special publication of the International Association of Sedimentologists.

Coope, G. R. 1977. Fossil coleopteran assemblages as sensitive indicators of climatic changes during the Devensian (Last) cold stage. *Philosophical Transactions of the Royal Society of London, Series B* 280: 313-40.

Cornish, R. 1981. Glaciers of the Loch Lomond Stadial in the western Southern Uplands of Scotland. *Proceedings of the Geologists' Association* 92: 105-14.

Craig, G. Y. 1983. *Geology of Scotland.* 2nd ed., 472. Edinburgh: Scottish Academic Press.

Cronin, T. M. 1988. Paleozoogeography of Postglacial Ostracoda from Northeastern North America. In *The Late Quaternary Development of the Champlain Sea Basin: Geological Association of Canada.* ed. N. R. Gadd, 125-44. Vol. Special Paper 35.

Cullingford, R. A. 1972. *Lateglacial and postglacial shoreline displacement in the Earn-Tay Area and Eastern Fife.* Unpublished PhD Thesis, University of Edinburgh.

Cullingford, R. A., C. J. Caseldine, and P. E. Gotts. 1980. Early Flandrian land and sea-level changes in Lower Strathearn. *Nature* 284: 159-61.

———. 1989. Evidence of early Flandrian tidal surges in Lower Strathearn, Scotland. *Journal of Quaternary Science* 4(1): 51-60.

Cullingford, R. A., and D. E. Smith. 1980. Late Devensian raised shorelines in Angus and Kincardineshire, Scotland. *Boreas* 9: 1980.

———. 1966. Lateglacial shorelines in eastern Fife. *Transactions of the Institute of British Geographers* 39: 31-51.

Cullingford, R. A., D. E. Smith, and C. R. Firth. 1991. The altitude and age of the Main Postglacial Shoreline in eastern Scotland. *Quaternary International* 9: 39-52.

Culver, S. J., and F. T. Banner. 1978. Foraminiferal assemblages as Flandrian palaeoenvironmental indicators. *Palaeogeography, Palaeoclimatology, Palaeoecology* 24: 53-72.

Dahl, E. 1956. Ecological salinity boundaries in poikilohaline waters. *Oikos* 7(1): 1-21.

Dawson, A. G. 1979. Former sea-level changes in the Scottish Hebrides. *Hebridean Naturalist* 3: 16-22.

———. 1980. The Low Rock Platform in western Scotland. *Proceedings of the Geologists' Association* 91: 339-44.

———. 1982. Lateglacial sea-level changes and ice-limits in Islay, Jura and Scarba, Scottish Inner Hebrides. *Journal of Geology* 18: 253-65.

———. 1984. Quaternary sea-level changes in Western Scotland. *Quaternary Science Review* 3: 345-68.

———. 1988. The Main Rock Platform (Main Lateglacial Shoreline) in Ardnamurchan and Moidart, western Scotland. *Scottish Journal of Geology* 24(2): 163-74.

———. 1992. *Ice Age Earth: Late Quaternary geology and climate.*, 293. London: Routledge.

Dawson, A. G., and S. Dawson. 1997. *The Quaternary of Islay and Jura: Field Guide*. Cambridge: Quaternary Research Association.

Dawson, A. G., D. Long, and D. E. Smith. 1988. The Storegga Slides: evidence from eastern Scotland for a possible tsunami. *Marine Geology* 88: 271-76.

Dawson, A. G., D. E. Smith, and D. Long. 1990. Evidence for a tsunami from a Mesolithic site in Inverness, Scotland. *Journal of Archaeological Science* 17: 509-12.

Dawson, S., and A. G. Dawson. 1997. Holocene relative sea level changes Gruinart, Isle of Islay. In *The Quaternary of Islay and Jura: Field Guide*. Eds. A. G. Dawson, and S. Dawson, 78-98. Cambridge: Quaternary Research Association.

Dawson, S., and D. E. Smith. 1997. Holocene relative sea-level changes on the margin of a glacio-isostatically uplifted area: an example from northern Caithness, Scotland. *The Holocene* 7, no. 1: 59-77.

de Rijk, S. 1995. Agglutinated foraminifera as indicators of salt marsh development in relation to late Holocene sea level rise. Amsterdam: University of Amsterdam.

de Wolf, H. 1982. *Method of coding of ecological data from diatoms for computer utilization.* Geological Survey of the Netherlands, Haarlem.

de Wolf, H., and L. Denys. 1993. *Actinoptychus splendens* (Shadbolt) Ralfs (Bacillariophyceae): a biostratigraphic marker for the later part of the Holocene coastal deposits along the southern North Sea. *Hydrobiologia* 269/270: 153-58.

Denton, G. H., and T. J. Hughes. 1981. *The last great ice sheets.*, 484. New York: John Wiley & Sons.

Devoy, R. J. N. 1979. Flandrian sea level changes and vegetational history of the lower Thames estuary. *Philosophical Transactions of the Royal Society of London, Series B* 285: 355-407.

———. 1982. Analysis of the geological evidence for Holocene sea-level movements in southeast England. *Proceedings of the Geologists' Association* 93, no. 1: 65-90.

———. 1987. Introduction: First Principals and the Scope of Sea-surface Studies. In *Sea surface studies.* ed. R. J. N. Devoy, 1-32. Beckenham: Croom Helm.

———. 1991. The study of inferred patterns of Holocene sea-level change from Atlantic and other European coastla margins as a means of testing models of Earth crustal behaviour. In *Glacial Isostasy, sea level and mantle rheology.* eds. R. Sabadini, K. Lambeck, and E. Boschi, 213-35. London: Kluwer Academic Publishers.

Dickson, J. H., D. A. Stewart, R. Thompson, G. Turner, M. S. Baxter, N. D. Drndarsky, and J. Rose. 1978. Palynology, palaeomagnetism and radiometric dating of Flandrian marine and freshwater sediments of Loch Lomond. *Nature* 274: 548-53.

Dimbleby, G. W. 1957. Pollen analysis of terrestrial soils. *New Phytologist* 56: 12-28.

Donner, J. J. 1959. The late- and post-glacial raised beaches in Scotland. *Annal. Acad. Sci. Fenn.* 53: 1-25.

———. 1963. The Late- and Post-glacial raised beaches in Scotland II. *Ann. Acad. Scient. Fennicæ* 68, no. Series A: 4-13.

———. 1970. Land/sea level changes in Scotland. *Studies in the vegetational history of the British Isles.* eds. M. J. C. Walker, and R. G. West, 23-40. Cambridge: Cambridge University Press.

Du Saar, A. 1967. Results and problems in diatom investigation at the geological survey in Haarlem. *Geologie En Mijnbouw* 46: 105-8.

Dumayne, L. 1992. *Late Holocene Palaeoecology and Human Impact on the environment of Northern Britain.* Unpublished PhD Thesis, University of Southampton.

Edwards, K. J. 1981. The seperation of *Corylus* and *Myrica* pollen in modern and fossil samples. *Pollen et Spores*, **22**, 205-218.

Edwards, K. J. 1990. Fire and the Scottish Mesolithic. In Vermeersch, P. M. and Van Peer, P. (eds.) *Contributions to the Mesolithic in Europe*. Leuven: Leuven University Press, 71-79.

Edwards, K. J., K. R. Hirons, and P. J. Newell. 1991. The palaeoecological and prehistoric context of minerogenic layers in blanket peat: a study from Loch Dee, southwest Scotland. *The Holocene* 1(1): 29-39.

Eyles, N., and A. M. McCabe. 1989. The Late Devensian (<22,000 BP) Irish Sea basin: the sedimentary record of a collapsed ice sheet margin. *Quaternary Science Reviews* 8: 307-51.

Faegri, K., and J. Iversen. 1989. *Textbook of pollen analysis.* 4th ed. Chichester: Wiley and Sons.

Fairbanks, R. G. 1990. The age and origin of the "Younger Dryas climate event" in Greenland ice cores. *Paleoceanography* 5: 937-48.

Fairbanks, R. G., C. D. Charles, and J. D. Wright. 1992. Origin of global meltwater pulses. In *Radiocarbon after four decades: An interdisciplinary Perspective.* eds. R. E. Taylor, A. Long, and R. S. Kra, 596. New York: Springer-Verlag.

Fairbridge, R. W. 1983. Isostasy and Eustasy. In *Shorelines and Isostasy.* eds. D. E. Smith, and A. G. Dawson, 3-28. London: Academic Press.

Firth, C. R. 1984. *Raised shorelines and ice limits in the inner Moray Firth and Loch Ness areas, Scotland.* Unpublished PhD Thesis, Coventry (Lanchester) Polytechnic.

Firth, C. R., and B. A. Haggart. 1989. Loch Lomond Stadial and Flandrian shorelines in the Inner Moray Firth area, Scotland. *Journal of Quaternary Science* 4: 37-59.

Firth, C. R., D. E. Smith, and R. A. Cullingford. 1993. Late Devensian and Holocene Glacio-isostatic Uplift Patterns in Scotland. *Neotectonics: Recent Advances.* eds. L. A. Owen, I. Stewart, and C. Vita-Finzi, 1-14. Cambridge: Quaternary Research Association.

Fisher, R. A., A. S. Corbet, and C. B. Williams. 1943. The relationship between the number of species and the number of individuals in a random sample of an animal population. *Journal of Animal Ecology* 12: 42-58.

Frausum, A. V., and K. Wouters. 1990. Ostracoda from Holocene calcareous tufa deposits in southern Belgium: a palaeoenvironmental analysis. In *Ostracoda and Global Events.* eds. R. C. Whatley, and C. Maybury, 505-11. London: Chapman & Hall.

Fries, M., and U. Hafsten. 1965. Asbjornsen's peat sampler the prototype of the Hiller sampler. *Geologiska Föreningens i Stockholm Förhandlingar* 87: 307-13.

Gaposchkin, E. M. 1973. Satellite dynamics. In *Smithsonian standard earth III.* ed. E. M. Gaposchkin, 85-192. Vol. 353. Smithsonian Astronomical Observatory Special Report.

Garbett, G. G. 1981. The Elm Decline: the depletion of a resource. *New Phytologist,* **88**, 573-585.

Gehrels, W. R., D. F. Belknap, and J. T. Kelley. 1996. Integrated high-precision analyses of Holocene relative sea-level changes: Lessons from the coast of Maine. *GSA Bulletin* 108(9): 1073-88.

Godwin, H. 1943. Coastal peat-beds of the British Isles and North Sea. *Journal of Ecology* 31(2): 199.

———. 1975. *The History of the British Flora.* 2nd ed., 541. Cambridge: Cambridge University Press.

———. 1975. *History of the British Flora: A factual basis for phytogeography.* 2nd ed., 541. Cambridge: Cambridge University Press.

———. 1940. Pollen analysis and forest history in England and Wales. *New Phytologist* 39: 370-400.

———. 1956. Studies of the Post-glacial history of British vegetation. The Meare Pool region of the Somerset Levels. *Philosophical Transactions* B 239: 161.

Godwin, H., and E. H. Willis. 1961. Cambridge University natural radiocarbon measurements II. *Radiocarbon* 3: 60-76.

Gray, J. M. 1995. Influence of Southern Upland ice on glacio-isostatic rebound in Scotland: the Main Rock Platform in the Firth of Clyde. *Boreas* 24: 30-36.

———. 1974. Lateglacial and postglacial shorelines in western Scotland. *Boreas* 3: 129-38.

———. 1978. Low-level shore platforms in the south-west Scottish Hoghlands: altitude, age and correlation. *Transactions of the Institute of British Geographers, New Series* 3: 151-64.

Gray, J. M., and M. Ivanovich. 1988. Age of the Main Rock Platform, western Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology* 68: 337-45.

Gray, J. M., and J. J. Lowe. 1977. The Scottish Lateglacial environment: a synthesis. *Studies in the Scottish Lateglacial Environment.* J. M. Gray, and J. J. Lowe, 163-81. Oxford: Pergamon Press.

Greensmith, J. T., and E. V. Tucker. 1986. Compaction and consolidation. *Sea-level research: a manual for the collection and evaluation of data.* ed. O. van de Plassche, 591-603. Norwich: Geo Books.

Griffiths, H. I. 1995. *The application of freshwater Ostracoda to the study of Late Quaternary palaeoenvironments in north-western Europe.* Unpublished PhD Thesis, University of Wales, Cardiff.

———. 1995. European Quaternary Freshwater Ostracoda: a Biostratigraphic and Palaeobiogeographic Primer. *Scopolia* 34: 1-168.

Griffiths, H. I., and J. G. Evans. 1995. An annotated check-list of British Pleistocene, Holocene and modern freshwater ostracods. *Journal of Micropalaeontology* 14: 59-65.

Griffiths, H. I., and D. S. Martin. 1993. The spatial distribution of benthic ostracods in the profundal zone of Loch Ness. *The Scottish Naturalist* 105: 137-47.

Griffiths, H. I., D. S. Martin, A. J. Shine, and J. G. Evans. 1993. The ostracod fauna (Crustacea, Ostracoda) of the profundal benthos of Loch Ness. *Hydrobiologia* 254: 111-17.

Griffiths, H. I., V. Ringwood, and J. G. Evans. 1994. Weichselian Late-glacial and early Holocene molluscan and ostracod sequences from lake sediments at Stellmoor, north Germany. *Arch. Hydrobiol./Suppl. 99* 3: 357-80.

Grimm, E. 1991. Tilia 1.08/Tilia*graph 1.16. Illonois State Museum, Illonois.

Haggart, B. A. 1982. *Flandrian sea-level changes in the Moray Firth area.* Unpublished PhD Thesis, University of Durham.

———. 1987. Relative sea-level changes at a site in the Beauly Firth area, Scotland. In *Sea-level changes.* eds. I. Shennan, and M. J. Tooley, 67-108. Blackwell.

———. 1986. Relative sea-level changes in the Beauly Firth, Scotland. *Boreas* 15: 191-207.

———. 1988. A review of radiocarbon dates on peat and wood from Holocene coastal sedimentary sequences in Scotland. *Scottish Journal of Geology* 24(2): 125-44.

———. 1989. Variations in the pattern and rate of isostatic uplift indicated by a comparison of Holocene sea-level curves from Scotland. *Journal of Quaternary Science* 4: 67-76.

Hall, A. M. 1984. Introduction. In *Buchan Field Guide.* ed. A. M. Hall, 27-45. Cambridge: Quaternary Research Association.

———. 1995. Was North-West Lewis glaciated during the Late Devensian? *Quaternary Newsletter* 76: 1-7.

Hall, A. M., and A. J. A. Bent. 1990. The limits of the last British ice-sheet in Northern Scotland and the adjacent shelf. *Quaternary Newsletter* 61: 2-21.

Hall, A. M., and G. Whittington. 1989. Late Devensian glaciation of southern Caithness. *Scottish Journal of Geology* 25: 307-24.

Harkness, D. D., and H. W. Wilson. 1979. Scottish Universities Research and Reactor Centre Radiocarbon Measurements III. *Radiocarbon* 23: 252-304.

Haslett, S. K. 1997. Late Quaternary foraminiferal biozonation and its implications for the relative sea-level history of Gruinart flats, Islay. In *The Quaternary of Islay and Jura.* eds. A. G. Dawson, and S. Dawson, 99-104. Cambridge: Quaternary Research Association.

Haynes, J. R. 1973. Cardigan Bay recent Foraminifera. *Bulletin of the British Museum (Natural History) Zoology* Supplement 4: 1-245.

———. 1981. *Foraminifera.*, 433. London: Macmillan.

Haynes, J. R., and M. Dobson. 1969. Physiography, foraminifera and sedimentation in the Dovey Estuary (Wales). *Geological Journal* 6(2): 217-56.

Haynes, J. R., R. J. Kiteley, R. C. Whatley, and P. J. Wilks. 1977. Microfaunas, microfloras and the environmental stratigraphy of the Late Glacial and Holocene in Cardigan Bay. *Geological Journal* 12(2): 129-58.

Healy, M. G. 1995. The lithostratigraphy and biostratigraphy of a Holocene coastal sediment sequence in Marazion Marsh, west Cornwall, U.K. with reference to relative sea-level movements. *Marine Geology* 124: 237-52.

Henderson, P. A. 1990. *Freshwater Ostracods: keys and notes for the identification of the species.*, 228. Synopses of the British Fauna (New Series), eds. D. M. Kermack, and R. S. K. Barnes, 42. Oegstgeest: Dr. W. Backhuys.

Hendey, N. I. 1964. *An introductory account of the smaller algae of British coastal waters, part V, Bacillariophyceae.* London: Her Majesty's Stationary Office.

Heyworth, A. 1978. Submerged forests around the British Isles: their dating and relevance as indicators of post-glacial land and sea level changes. In *Dendrochronology in Europe.* ed. J. Fletcher, 279-88. Oxford: BAR International Series.

Heyworth, A., and C. Kidson. 1982. Sea-level changes in southwest England and Wales. *Proceedings of the Geologists' Association* 93: 91-111.

Hinton, A. C. 1992. Palaeotidal changes within the area of the Wash during the Holocene. *Proceedings of the Geologists' Association* 103, no. 3: 259-72.

Holmes, J. A. 1992. Nonmarine ostracods as Quaternary palaeoenvironmental indicators. *Progress in Physical Geography* 16(4): 405-31.

Hoppe, G. 1965. Submarine peat in the Shetland Islands. *Geografiska Annaler* 47A: 195-203.

Horne, D. J. 1980. *Recent Ostracoda from the Severn Estuary and Bristol Channel.* Unpublished PhD Thesis, University of Bristol.

———. 1982. The vertical distribution of phytal ostracods in the intertidal zone at Gore Point, Bristol Channel, U.K. *Journal of Micropalaeontology* 1: 71-84.

Huddart, D. 1992. Coastal environmental changes and morphostratigraphy in southwest Lancashire, England. *Proceedings of the Geologists' Association* 103(3): 217-36.

Huntley, B. and Birks, H. J. B. 1983. *An atlas of past and present pollen maps for Europe: 0-13000 years ago.* Cambridge: Cambridge University Press.

Hustedt, F. 1927-1966. Die Kieselalgen Deutschlands, Österreichs und der Schweiz unter Besucksichtigung der ubrigen Lander Europas sowie der angrensenden Meeresgebiete. In *Kryptogramen - Flora von Deutschland.* ed. L. RabenhorstLeipzig, Germany.

———. 1953. Die Systematik der Diatomeen in ihren Beziehungen zur Geologie und Ökologie nebst einer Revision des Halobian-systems. *Sv. Bot. Tidskr.* 47: 274-344.

———. 1957. Die Diatomeen des Flussytems der Weser im Gebeit der Hansestadt Bremen. *Abh. Naturwiss. Verein.* 34(3): 173-440.

Hyvärinen, H. 1978. Use and definition of the term Flandrian. *Boreas* 7: 182.

Innes, J. B., and I. Shennan. 1994. Glenancross. In *Late Quaternary Coastal Records of Rapid Change, Field Guide, IGCP Project 367.* ed. I. Shennan, 26. Durham: Environmental Research Centre, University of Durham.

Jacobson, G. L. Jr., and R. H. W. Bradshaw. 1981. The selection of sites for palaeo-vegetational studies. *Quaternary Research* 16: 80-96.

Jamieson, T. F. 1865. On the history of the last geological changes in Scotland. *Quatererly Journal of the Geological Society of London* 21: 161-203.

Jansen, J. H. F. 1976. Late Pleistocene and Holocene history of the northern North Sea, based on acoustic reflection records. *The Netherlands Journal of Sea Research* 10: 1-43.

Jardine, W.G. 1964. Post-glacial sea-levels in south-west Scotland. *Scottish Geographical Magazine* 80: 5-11.

———. 1967. Sediments of the Flandrian transgression in south-west Scotland: terminology and criteria for facies distinction. *Scottish Journal of Geology* 3: 221-26.

———. 1971. Form and age of late Quaternary shorelines and coastal deposits of south-west Scotland; critical data. *Quaternaria* 14: 103-14.

———. 1975a. Chronology of Holocene marine transgression and regression in south-western Scotland. *Boreas* 4: 173-96.

———. 1975b. The determination of former sea levels in areas of large tidal range. In *Quaternary Studies.* eds. R. P. Suggate, and M. M. Cresswell, 163-68. Wellington: The Royal Society of New Zealand.

———. 1976. Some problems in plotting the mean surface level of the North Sea and the Irish Sea during the last 15,000 years. *Geologiska Föreningens i Stockholm Förhandlingar* 98: 78-82.

———. 1977. The Quaternary marine record in southwest Scotland and the Scottish Hebrides. In *The Quaternary History of the Irish Sea.* eds. C. Kidson, and M. J. Tooley, 99-118. Liverpool: Seal House Press.

———. 1978. Radiocarbon ages of raised-beach shells from Oronsay, Inner Hebrides, Scotland: a lesson in interpretation and deduction. *Boreas* 7: 183-96.

———. 1980. Holocene raised coastal sediments and former shorelines of Dumfriesshire and Eastern Galloway. *Transactions of the Dumfriesshire and Galloway Natural History and Antiquarian Society* 55: 1-59.

———. 1981-1982. The determination of former shoreline positions in areas of large tidal range, with examples taken mainly from Scotland. *Bulletin De L'Association Française Pour L'Étude Du Quaternaire* : 67-70.

———. 1986. Determination of altitude. In *Sea-level research: a manual for the collection and evaluation of data.* ed. O. van de Plassche, 569-90. Norwich: Geo Books.

Jardine, W. G., and A. Morrison. 1976. The archaeological significance of Holocene coastal deposits in south-western Scotland. In *Geoarchaeology: Earth Science and the Past.* eds. D. A. Davidson, and M. L. Shackley, 175-95. London.

Jelgersma, S. 1961. Holocene sea level changes in the Netherlands. *Meded. Geol. Sticht.* Serie C, VI(7): 1-100.

Jennings, A. E., and A. R. Nelson. 1992. Foraminiferal assemblage zones in Oregon tidal marshes - relation to marsh floral zones and sea level. *Journal of Foraminiferal Research* 22(1): 13-29.

Jensen, K. A., and K. L. Knudsen. 1988. Quaternary foraminiferal stratigraphy in boring 81/29 from the central North Sea. *Boreas* 17: 273-87.

Jones, R. L. 1988. The impact of early man on coastal plant communities in the British Isles. In *Archaeology and the Flora of the British Isles.* ed. M. Jones, 96-106. Oxford: University Committee for Archaeology.

Jones, V. J., and A. C. Stevenson. 1993. Round Loch of Glenhead. In *Quaternary of Scotland.* eds. J. E. Gordon, and D. G. Sutherland, 609-13. London: Chapman & Hall.

Jowsey, P. C. 1966. An improved peat sampler. *New Phytologist* 65: 245-48.

Kamiya, T. 1988. Morphological and ethological adaptions of Ostracoda to microhabitats in Zostera beds. In *Evolutionary Biology of Ostracoda. Proceedings of the Ninth International Symposium on Ostracoda*, eds. T. Hanai, N. Ikeya, and K. IshizakiTokyo: Kodansha Ltd.

Kapsner, W. R., R. B. Alley, C. A. Shuman, S. Amandkrishnan, and P. M. Grootes. 1995. Dominant influence of atmospheric circulation on snow accumulation in Greenland over the past 18,000 years. *Nature* 373: 52-54.

Kaye, C. A., and E. S. Barghoorn. 1964. Late Quaternary sea-level change and crustal rise at Boston, Massachusetts, with notes on the autocompaction of peat. *Geological Society of America Bulletin* 75: 63-80.

Keen, D. H., J. E. Robinson, R. G. West, F. Lowry, D. R. Bridgland, and N. D. W. Davey. 1990. The fauna and flora of the March Gravels at Northam Pit, Eye, Cambridgeshire, England. *Geological Magazine* 127(5): 453-65.

Kennet, J. P., and N. J. Shackleton. 1975. Laurentide ice sheet meltwater recorded in Gulf of Mexico deep-sea cores. *Science* 188: 147-50.

Kerney, M. P. 1976. A list of the fresh and the brackish water mollusca of the British Isles. *Journal of Conchology* 29: 26-28.

Kidson, C. 1982. Sea level changes in the Holocene. *Quaternary Science Reviews* 1: 121-51.

Kidson, C., D. D. Gilbertson, J. R. Haynes, A. Heyworth, C. E. Hughes, and R. C. Whatley. 1978. Interglacial marine deposits of the Somerset Levels, South West England. *Boreas* 7: 215-28.

Kidson, C., and A. Heyworth. 1973. The Flandrian sea-level rise in the Bristol Channel. *Proc. Ussher. Soc.* 2: 565-84.

Kilenyi, T. I. 1969. The problems of ostracod ecology in the Thames Estuary. In *The Taxonomy, Morphology and Ecology of Recent Ostracoda.* ed. J. W. Neale, 251-67. Edinburgh: Oliver & Boyd.

King, C. A. M., and P. T. Wheeler. 1963. The raised beaches of the north coast of Sutherland, Scotland. *Geological Magazine* 100: 299-320.

Knudsen, K. L. 1992. A long marine Eemian-Weichselian shelf record in North Denmark, Scandinavia. In *Start of a Glacial.* eds. G. J. Kukla, and E. Went, 157-71. Vol. 13. Berlin: Springer-Verlag.

Knudsen, K. L., and W. E. N. Austin. 1996. Late glacial foraminifera. *Late Quaternary Palaeoceanography of the North Atlantic Margins.* eds. J. T. Andrews, W. E. N. Austin, H. Bergsten, and A. E. Jennings, 7-10. Geological Society Special Publication No. 111.

Knudsen, K. L., and D. N. Penney. 1987. *Danmarks Geologiske Undersøgelse, Serie B* NR.10: 9-30.

Koerner, R. M., and D. A. Fisher. 1990. A record of Holocene summer climate from a Canadian high-Arctic ice core. *Nature* 343: 630-631.

Kolbe, R. W. 1927. Zur Ökologie, Morphologie und Systematik der Brackwasser-Diatomeen. In *Pflanzenf.* ed. R. KolkwitzVol. 7. Jena: G. Fischer.

Krammer, K., and H. Lange-Bertalot. 1991. *Bacillariophyceae.* (Teil 1-4) ed. Stuttgart: Gustav Fischer Verlag.

Kromer, B., B. Becker, P. Trimborn, and M. Spurk. 1995. Tree-ring based 14C calibration and stable isotope series at the YD/PB boundary. In *The Younger Dryas.* eds. S. R. Trolestra, J. E. van Hinte, and G. M. Ganssen, 224.

Kroon, D., and W. E. N. Austin. 1995. High resolution marine records of the last glacial/interglacial transition from the Hebridean margin, N.W. Scotland. In *The Younger Dryas.* eds. S. R. Trolestra, J. E. van Hinte, and G. M. Ganssen, 125-30.

Lambeck, K. 1990. Glacial rebound, sea-level change and mantle viscosity. *Q. Jl R. Astr. Soc.* 31: 1-30.

———. 1991a. Glacial rebound and sea level change in the British Isles. *Terra Nova* 3: 379-89.

———. 1991b. A model for Devensian and Flandrian glacial rebound and sea-level change in Scotland. In *Glacial Isostasy, sea level and mantle rheology.* eds. R. Sabadini, K. Lambeck, and E. Boschi, 33-61. Dordrecht: Kluwer.

———. 1993a. Glacial rebound of the British Isles-I. Preliminary model results. *Geophysics Journal International* 115: 941-59.

———. 1993b. Glacial rebound of the British Isles-II. A high-resolution, high-precision model. *Geophysics Journal International* 115: 960-990.

———. 1995a. Glacial isostasy and water depths in the Late Devensian and Holocene on the Scottish Shelf west of the Outer Hebrides. *Journal of Quaternary Science* 10(1): 83-86.

———. 1995b. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society, London* 152: 437-48.

Leoblich, A. R. Jr., and H. Tappan. 1988. *Foraminiferal Genera and their Classification.* New York: van Nostrand Reinhold.

———. 1974. Recent advances in the classification of the Foraminiferida. In *Foraminifera.* eds. R. H. Hedley, and C. G. Adams, 1-53. Vol. 1. London and New York: Academic Press.

Libby, W. 1965. *Radiocarbon Dating.*, 175. Chicago: University of Chicago Press.

Lie, S. E., B. Stabell, and J. Mangerud. 1983. Diatom stratigraphy related to Late Weichselian sea-level changes in Sunnmøre, Western Norway. *Norges Geol. Unders.* 380: 203-19.

Löffler, H. 1986. Ostracod analysis. In *Handbook of Holocene Palaeoecology and Palaeohydrology.* ed. B. E. Berglund, 693-702. John Wiley & Sons Ltd.

Long, A. J. 1992. Coastal responses to changes in sea-level in the East Kent Fens and southeast England, UK over the last 7500 years. *Proceedings of the Geologists' Association* 103(3): 187-99.

Long, D., A. J. A. Bent, R. Harland, D. M. Gregory, D. K. Graham, and A. C. Morton. 1986. Late Quaternary palaeontology, sedimentology and geochemistry of a vibrocore from the Witch Ground Basin, Central North Sea. *Marine Geology* 73: 109-23.

Lord, A. R. 1980. Interpretation of the Lateglacial Marine Environment of NW Europe by Means of Foraminiferida. In *Studies in the Lateglacial of North-West Europe*. eds. J. J. Lowe, J. M. Gray, and J. E. Robinson, 103-14. Oxford: Pergamon Press.

———. 1980. Weichselian (Late Quaternary) ostracods from the Sandnes Clay, Norway. *Geological Magazine* 117(3): 227-42.

Lord, A. R., J. E. Robinson, and S. G. Moutzourides. 1993. Ostracoda from Holsteinian Deposits in the Hamburg Area. *Geol. Jb.* A 138: 127-45.

Lowe, J. J., G. R. Coope, C. Sheldrick, D. D. Harkness, and M. J. C. Walker. 1995. Direct comparison of UK temperatures and Greenland snow accumulation rates. *Journal of Quaternary Science* 10(2): 175-80.

Lowe, J. J., and M. J. C. Walker. 1984. *Reconstructing Quaternary Environments.*, 389. Harlow: Longman Scientific & Technical.

Lozek, V. 1986. Mollusca analysis. In *Handbook of Holocene Palaeoecology and Palaeohydrology*. ed. B. E. Berglund, 729-40. John Wiley & Sons Ltd.

Macan, T. T. 1977. *A key to the British fresh- and brackish-water Gastropods with notes on their ecology*. 4th ed., 45Freshwater Biological Association.

MacFarlane, I. C. 1965. The consolidation of peat - a literature review. Technical Paper 195, Division of Building Research, N. R. C., Ottawa.

Mangerud, J., S. T. Anderson, B. E. Berglund, and J. J. Donner. 1974. Quaternary stratigraphy of Norden, a proposal for terminology and classification. *Boreas* 3: 109-28.

Marshall, J. R. 1962. The morphology of the upper Solway salt marshes. *Scottish Geographical Magazine* 78: 81-99.

Matthews, S. C. 1973. Notes on open nomenclature and on synonymy lists. *Palaeontology* 16: 713-19.

Maynard, D. J. 1994a. Archaeological discoveries in the dune system at Brighouse Bay. *Transactions of the Dumfriesshire and Galloway Natural History and Antiquarian Society* 69: 13-34.

McCave, I. N. and J. P. M. Syvitski 1991. Principals and methods of geological particle size analysis. In *Principals, methods and applications of particle size analysis*. ed. J. P. M. Syvitski, 1-3. UK: Cambridge University Press.

McGregor, D. L. 1969. The reproductive potential, life history and parasitism of the freshwater ostracod *Darwinula stevensoni* (Brady and Robertson). In *The Taxonomy, Morphology and Ecology of Recent Ostracoda.* ed. J. W. Neale, 194-221. Edinburgh: Oliver & Boyd.

McIntire, C. D., and W. W. Moore. 1977. Marine littoral diatoms - Ecological considerations. In *The Biology of Diatoms.* ed. D. WernerBerkeley, California: University of California.

Mighall, T. M., and F. M. Chambers. 1995. Holocene vegetation history and human impact at Bryn y Castell, Snowdonia, north Wales. *New Phytologist* 130: 299-321.

Miller, A. A. L., D. B. Scott, and F. S. Medioli. 1982. *Elphidium excavatum* (Terquem): ecophenotype versus subspecific variation. *Journal of Foraminiferal Research* 12(2): 116-44.

Mizen, V. 1986. *Ecostratigraphy of Quaternary non-marine ostracoda from the Somerset Levels.* Unpublished M.Sc. Thesis, University of Wales, Aberystwyth.

Moar, N. T. 1969. Late Weichselian and Flandrian pollen diagrams from south-west Scotland. *New Phytologist* 68: 433-67.

Moe, D. and Rackham, O. 1992. Pollarding and a possible explanation of the neolithic elmfall. *Vegetation History and Archaeobotany*, **1**, 63-68.

Moore, P. D. 1988. The development of moorlands and upland mires. In *Archaeology and the Flora of the British Isles.* ed. M. Jones, 116-22. Oxford: University Committee for Archaeology.

Moore, P. D., J. A. Webb, and M. E. Collinson. 1991. *Pollen analysis.* 2nd ed., 216. Oxford: Blackwell Scientific Publications.

Mörner, N-A. 1976. Eustatic changes during the last 8,000 years in view of radiocarbon calibration and new information from the Kattegat region and other northwestern European coastal areas. *Palaeogeography, Palaeoclimatology, Palaeoecology* 19: 63-85.

———. 1980a. Eustasy and geoid changes as a function of core/mantle changes. In *Earth Rheology, Isostasy and Eustasy.* ed. N-A. Mörner, 535-54. Chichester: John Wiley & Sons.

———. 1980b. Late Quaternary sea-level changes in north-western Europe: a synthesis. *Geologiska Föreningens i Stockholm Förhandlingar* 100(4): 381-400.

———. 1983. Differential Holocene sea level changes over the globe: evidence for glacial eustasy, geoidal eustasy and crustal movements. *Abstracts: International Symposium on Coastal Evolution in the Holocene, Tokyo 1983* : 93-96. 248.

Morrison, A., and C. Bonsall. 1989. The early post-glacial settlement of Scotland: a review. In *The Mesolithic in Europe.* ed. C. Bonsall, 134-42. Edinburgh: John Donald.

Morrison, J., D. E. Smith, R. A. Cullingford, and R. L. Jones. 1981. The culmination of the Main Postglacial Transgression in the Firth of Tay area, Scotland. *Proceedings of the Geologists' Association* 92: 197-209.

Mostafawi, N. 1990. Ostracods in late Pleistocene and Holocene sediments from the Fram Strait, eastern Arctic. In *Ostracoda and Global Events.* eds. R. C. Whatley, and C. Maybury, 489-94. London: Chapman & Hall.

Mudie, P. J. 1982. Pollen distribution in recent marine sediments, eastern Canada. *Canadian Journal of Earth Sciences* 19: 729-47.

Murray, J. W. 1973. *Distribution and Ecology of Living Benthic Foraminiferids.*, 288. London: Heinemann.

———. 1976. Comparative studies of living and dead benthic foraminiferal distributions. *Foraminifera* 2: 45-109.

———. 1979. *British Nearshore Foraminiferids.* London: Academic Press.

———. 1982. Benthic foraminifera: the validity of living, dead or total assemblages for the interpretation of palaeoecology. *Journal of Micropalaeontology* 1: 137-40.

———. 1991. *Ecology and palaeoecology of benthic foraminifera.*, 397. England: Longman Group UK Limited.

Murray, J. W., and A. B. Hawkins. 1976. Sediment transport in the Severn Estuary during the past 8000-9000 years. *Journal of the Geological Society, London* 132: 385-98.

Nakada, M., and K. Lambeck. 1989. Late Pleistocene and Holocene sea-level change in the Australian region and mantle rheology. *Geophysical Journal* 96: 497-517.

Neale, J. W. 1964. Some factors influencing the distribution of Recent British Ostracoda. *Pubbl. Staz. Zool. Napoli* 33 suppl.: 247-307.

Nelson, A. R., and K. Kashima. 1993. Diatom zonation in southern Oregon tidal marshes relative to vascular plants, foraminifera and sea-level. *Journal of Coastal Research* 9(3): 673-97.

Nichols, H. 1967. Vegetational change, shoreline displacement and the human factor in the late Quaternary history of south-west Scotland. *Transactions of the Royal Society of Edinburgh* 67: 145-87.

Okeland, J. 1969. Distribution and ecology of the Freshwater snails (Gastropods) of Norway. *Malacologia* 9: 143-51.

Olsson, I. U. 1986. A study of errors in ^{14}C dates of peat and sediment. *Radiocarbon* 28(2A): 429-35.

Orford, J. D., R. W. G. Carter, and S. C. Jennings. 1991. Coarse clastic barrier environments: evolution and implications for Quaternary sea level interpretation. *Quaternary International* 9: 87-104.

Palmer, A. J. M., and W. H. Abbott. 1986. Diatoms as indicators of sea-level change. In *Sea-level research: a manual for the collection and evaluation of data.* ed. O. van de Plassche, 457-87. Norwich: Geobooks.

Pantin, H. M. 1975. Quaternary sediments of the north-eastern Irish Sea. *Quaternary Newsletter* 17: 7-9.

Patterson, W. A., K. J. Edwards, and D. N. Maguire. 1987. Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* 6: 3-23.

Peacock, J. D. 1975. Scottish late- and post-glacial marine deposits. In *Gemmell, A.M.D.* ed. Quaternary Studies in North East Scotland, 45-48. Aberdeen: Department of Geography, University of Aberdeen.

———. 1980. Glaciation of the Outer Hebrides: a reply. *Scottish Journal of Geology* 16: 87-89.

———. 1981. Scottish Late-glacial Marine Deposits and their Environmental Significance. *Ecology and Palaeoecology of Benthic Foraminifera.* eds. J. W. Neale, and J. Flenley, 222-36. Oxford: Pergamon Press.

———. 1991. Glacial deposits of the Hebridean region. In *Glacial Deposits in Great Britain and Ireland.* eds J. Ehlers, P. L. Gibbard, and J. Rose, 109-19. Rotterdam: A.A. Balkema.

———. 1993. Late Quaternary marine mollusca as palaeoenvironmental proxies: a compilation and assessment of basic numerical data for NE Atlantic species found in shallow water. *Quaternary Science Reviews* 12: 263-75.

Peacock, J. D., W. E. N. Austin, I. Selby, D. K. Graham, R. Harland, and I. P. Wilkinson. 1992. Late Devensian and Flandrian palaeoenvironmental changes on the Scottish continental shelf west of the Outer Hebrides. *Journal of Quaternary Science* 7: 145-62.

Peacock, J. D., D. K. Graham, J. E. Robinson, and I. P. Wilkinson. 1977. Evolution and Chronology of Lateglacial Marine Emvironments at Lochgilphead, Scotland. *Studies in the Scottish Lateglacial Environment.* eds. J. M. Gray, and J. J. Lowe, 89-100. Oxford: Pergamon Press.

Peacock, J. D., D. K. Graham, and I. P. Wilkinson. 1978. Late-glacial and post-glacial marine environments at Ardyne, Scotland, and their significance in the interpretation of the history of the Firth of Clyde sea area. *Report of the Institue of Geological Sciences* 78/17: 11.

Peacock, J. D., and D. D. Harkness. 1990. Radiocarbon ages and the full-glacial to Holocene transition in seas adjacent to Scotland and southern Scandinavia: a review. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 81: 385-96.

Peglar, S. and Birks, H. J. B. 1993. The mid-Holocene *Ulmus* fall at Diss Mere, south-east England - disease and human impact? *Vegetation history and Archaeobotany*, **2**, 61-68.

Penney, D. N. 1985. The Holocene marine sequence in the Løkken area of Vendyssel, Denmark. *Eiszeitalter Und Gegenwart* 35: 79-88.

———. 1987. Application of Ostracoda to sea-level studies. *Boreas* 16: 237-47.

———. 1990. Quaternary ostracod chronology of the central North Sea: the record from BH 81/29. *Cour. Forsch.-Inst. Seneckenberg* 123: 97-109.

———. 1993. Northern North Sea benthic Ostracoda: modern distribution and palaeoenvironmental significance. *The Holocene* 3(3): 241-54.

Pennington, W. 1975. The effect of neolithic man on the environment in northwest England: the use of absolute pollen diagrams. In *The effect of man on the landscape: the highland zone.* eds. J. G. Evans, S. Limbrey, and H. CleereCBA Research Report No. 11.

Pennington, W. 1977. Lake sediments and the Lateglacial environment in northern Scotland. In *Studies in the Scottish Lateglacial environment.* eds. J. M. Gray, and J. J. Lowe, 119-42. Oxford: Pergammon.

Perry, I. and Moore, P. D. 1987. Dutch elm disease as an analogue of Neolithic elm decline. *Nature*, **326**, 72-73.

Petersen, K. S. 1986. Marine molluscs as indicators of former sea-level stands. *Sea-level research: a manual for the collection and evaluation of data.* ed. O. van de Plassche, 129-55. Norwich: Geo Books.

Peypouquet, J-P. 1979-1980. Les Ostracodes et la recherche des paléorivages, indicateurs des niveaux marins. *Oceanis* 5: 273-81.

Phleger, F. B. 1967. Marsh foraminiferal patterns, Pacific Coast of America: Annals Instituto Biologico Universidad National Aut., Mexico 38. *Serie Ciencias Del. Mar y Limnologia* 1: 11-38.

Pielou, E. C. 1979. A quick method of determining the diversity of foraminiferal assemblages. *Journal of Paleontology* 53: 1237-42.

Pilcher, J. R. 1991. Radiocarbon Dating. In *Quaternary Dating Methods - A user's guide.* Technical Guide No.4 ed., eds. P. L. Smart, and P. D. Frances, 16-36. London: Quaternary Research Association.

Plater, A. J., and I. Shennan. 1992. Evidence of Holocene sea-level change from the Northumberland coast, eastern England. *Proceedings of the Geologists' Association* 103(3): 201-16.

Prince, H. E. 1988. "Late-glacial and Post-glacial sea-level movements in North Wales with particular reference to the techniques for the analysis and interpretation of unconsolidated estuarine sediments." University of Wales.

R.S.K. Environment Ltd. 1992. *Gas Interconnector Project, Draft Environmental Statement.*

Radle, N., C. M. Keister, and R. W. Battarbee. 1989. Diatom, pollen and geochemical evidence for the palaeosalinity of Medicine Lake, S. Dakota, during the Late Wisconsin and early Holocene. *Journal of Paleolimnology* 2: 159-72.

Reavell, P. E. 1980. A study of the diets of some British freshwater gastropods. *Journal of Conchology* 30: 253-71.

Richter, G. 1964. Zur Okologie der Foraminiferen II. Lebensraum und Lebenweise von *Nonion depressulum*, *Elphidium excavatum* und *Elphidium selseyense*. *Natur Und Museum, Frankfurt* 94: 421-30.

Ritchie, W. 1966. The Post-glacial rise in sea-level and coastal changes in the Uists. *Transactions of the Institute of British Geographers* 39: 79-86.

Robinson, J. E. 1980. The Marine Ostracod Record from the Lateglacial Period in Britain and NW Europe: A Review. In *Studies in the Lateglacial of North-West Europe.* eds. J. J. Lowe, J. M. Gray, and J. E. Robinson, 115-22. Pergamon Press.

Robinson, M. 1977. *Glacial limits, sea-level changes and vegetational development in part of Wester Ross.* Unpublished PhD Thesis, University of Edinburgh.

———. 1993. Microfossil analyses and radiocarbon dating of depositional sequences related to Holocene sea-level change in the Forth valley, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 84: 1-60.

Robinson, M., and C. K. Ballantyne. 1979. Evidence for a glacial readvance pre-dating the Loch Lomond Advance in Wester Ross. *Scottish Journal of Geology* 15: 271-77.

Rosenfeld, A. 1977. Die rezenten Ostracoden-Arten in der Ostsee (Recent Ostracode-species in the Baltic Sea). *Meyniana* 29: 11-49.

———. 1979. Seasonal Distributions of Recent Ostracodes from Kiel Bay, Western Baltic. *Meyniana* 31: 59-82.

Round, F. E. 1964. The diatom sequence in lake deposits: some problems of interpretation. *Verh. Internat. Verein. Limnol.* 15: 1012-20.

———. 1971. Benthic Marine Diatoms. *Oceanogr. Mar. Biol. Ann. Rev.* 9: 83-139.

Ruddiman, W. F., and L. K. Glover. 1975. Subpolar North Atlantic Circulation at 9300 yr BP: Faunal Evidence. *Quaternary Research* 5: 361-89.

Ruddiman, W. F., and A. McIntyre. 1973. Time-transgressive deglacial retreat of polar waters from the North Atlantic. *Quaternary Research* 3: 117-30.

Ruddiman, W. F., C. D. Sancetta, and A. McIntyre. 1977. Glacial/Interglacial response rate of subpolar North Atlantic waters to climatic change: the record in oceanic sediments. *Philosophical Transactions of the Royal Society of London, Series B* 280: 119-42.

Scaife, R., and A. Long. 1994. Evidence for Holocene sea-level changes at Caldicot Pit. In *Archaeology in the Severn Estuary*, ed. M. Bell. University of Wales, Lampeter.

Scott, D. B., and F. S. Medioli. 1986. Foraminifera as sea-level indicators. In *Sea-level research: a manual for the collection and evaluation of data.* ed. O van de Plassche, 435-56. Norwich: Geo Books.

———. 1978. Vertical zonations of marsh foraminifera as accurate indicators of former sea-levels. *Nature* 272: 528-31.

Seaward, D. R. 1990. *Distribution of the marine molluscs of north west Europe.* Peterborough: Nature Conservancy Council. pp114.

Sejrup, H. P., I. Aarseth, K. L. Ellingson, E. Reither, E. Jansen, R. Løvlie, A. Bent, J. Brigham-Grette, E. Larsen, and M. Stoker. 1987. Quaternary stratigraphy of the Fladen area, central North Sea: a multidisciplinary study. *Journal of Quaternary Science* 2: 35-58.

Sejrup, H. P., H. Haflidason, I. Aarseth, E. King, C. F. Forsberg, D. Long, and K. Rokoengen. 1994. Late Weichselian glaciation history of the northern North Sea. *Boreas* 23: 1-13.

Selby, I. 1989. *The Quaternary geology of the Hebridean continental margin.* Unpublished PhD Thesis, University of Nottingham.

Shennan, I. 1978. Global analysis and correlation of sea-level data. In *Sea surface studies*. ed. R. J. N. Devoy, 198-230. Beckenham: Croom Helm.

———. 1980. *Flandrian sea-level changes in the Fenland.* Unpublished PhD Thesis, University of Durham.

———. 1983. A problem of definition in sea-level research methods. *Quaternary Newsletter* 39: 17-19.

———. 1986a. Flandrian sea-level changes in the Fenland. I: The geographical setting and evidence of relative sea-level changes. *Journal of Quaternary Science* 1(2): 119-54.

———. 1986b. Flandrian sea-level changes in the Fenland. II: Tendecies of sea-level movement, altitudinal changes, and local and regional factors. *Journal of Quaternary Science* 1(2): 155-79.

———. 1989. Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science* 4(1): 77-89.

———. 1992. Late Quaternary sea-level changes and crustal movements in eastern England and eastern Scotland: an assessment of models of coastal evolution. *Quaternary International* 15/16: 161-73.

———. 1995. Sea-level and coastal evolution: Holocene analogues for future changes. *Coastal Zone Topics: Process, Ecology & Management* 1: 1-9.

Shennan, I., J. B. Innes, A. J. Long, and Y. Zong. 1994a. Holocene relative sea-level changes and coastal vegetation history at Kentra Moss, Argyll, Northwest Scotland. *Marine Geology* .

———. 1994b. Late Devensian and Holocene relative sea-level changes at Loch nan Eala, near Arisaig, northwest Scotland. *Journal of Quaternary Science* 9(3): 261-83.

———. 1993. Late Devensian and Holocene relative sea-level changes at Rumach, near Arisaig, northwest Scotland. *Norsk Geologisk Tidsskrift* 73: 161-74.

Shennan, I., M. M. Rutherford, J. B. Innes, and K. J. Walker. 1996. Late glacial sea level and ocean margin environmental changes interpreted from biostratigraphic and lithostratigraphic studies of isolation basins in northwest Scotland. In *Late Quaternary Palaeoceanography of the North Atlantic Margins*. eds. J. T. Andrews, W. E. N. Austin, H. Bergsten, and A. E. Jennings, 229-44. Geological Society Special Publication No.111.

Shennan, I., M. J. Tooley, and M. J. Haggart B. A. Davis. 1983. Analysis and interpretation of Holocene sea-level data. *Nature (Lond.)* 302: 404-6.

Sherrod, B. L., H. B. Rollins, and S. K. Kennedy. 1989. Subrecent intertidal diatoms from St. Catherines Island, Georgia: Taphonomic Implications. *Journal of Coastal Research* 5(4): 665-77.

Shi, S. 1995. *Observational and theoretical aspects of tsunami sedimentation.* Unpublished PhD Thesis, Coventry University.

Siddiqui, Q., and J. Milne. 1988. The palaeoecology of Ostracoda in late Pleistocene sediments from Borehole 85 GSC 1 in the western Beaufort Sea. In *Ostracoda and Global Events.* eds. R. C. Whatley, and C. Maybury, 495-504. London: Chapman & Hall.

Simmons, I. G., M. A. Atherden, P. R. Cundill, and R. C. Jones. 1975. Inorganic layers in soligenous mires of the North Yorkshire Moors. *Journal of Biogeography* 2: 49-56.

Simonsen, R. 1967. Diatoms as indicators in estuarine environments. *Veröffentl. Inst. Meeresforsch. Bremerhaven* 11: 287-91.

Sissons, J. B. 1966. Relative sea-level changes between 10,300 and 8,300 BP in part of the Carse of Stirling. *Transactions of the Institute of British Geographers* 39: 19-29.

———. 1967. *The Evolution of Scotland's Scenary.*, 259. Edinburgh: Oliver and Boyd Ltd.

———. 1974. The Quaternary of Scotland: a review. *Scottish Journal of Geology* 10: 311-37.

———. 1976. Lateglacial marine erosion in south east Scotland. *Scottish Geographical Magazine* 92: 17-92.

———. 1979a. The Loch Lomond advance in the Cairngorm mountains. *Scottish Geographical Magazine* 95: 66-82.

———. 1979b. The Loch Lomond Stadial in the British Isles. *Nature* 280: 199-203.

———. 1981. The last Scottish ice-sheet: facts and speculative discussion. *Boreas* 10: 1-17.

———. 1982. A former ice-dammed lake and associated glacier limits in the Achnasheen area, central Ross-shire. *Transactions of the Institute of British Geographers, New Series* 7: 98-116.

———. 1983. Shorelines and Isostasy in Scotland. In *Shorelines and Isostasy.* eds. D. E. Smith, and A. G. Dawson, 209-25. London: Academic Press.

Sissons, J. B., and C. L. Brooks. 1971. Dating of early postglacial land and sea-level changes in the western Forth Valley. *Nature of Physical Science* 94: 165-75.

Sissons, J. B., and D. E. Smith. 1965. Peat bogs in a post-glacial sea and a buried beach in the western part of the Carse of Stirling. *Scottish Journal of Geology* 1: 247-55.

Sissons, J. B., D. E. Smith, and R. A. Cullingford. 1966. Late-glacial and post-glacial shorelines in south-east Scotland. *Transactions of the Institute of British Geographers* 39: 9-18.

Sissons, J. B., and M. J. C. Walker. 1974. Late glacial site in the central Grampian Highlands. *Nature* 249: 822-24.

Skempton, A. W. 1970. The consolidation of clays by gravitational compaction. *Quarterly Journal of the Geological Society of London* 125: 373-411.

Smith, A. G. 1984. Newferry and the Boreal-Atlantic transition. *New Phytologist* 98: 35-55.

Smith, D. E. 1968. Post-glacial displaced shorelines in the surface of the carse clay on the north bank of the river Forth, in Scotland. *Zeitschrift Für Geomorphologie* 4: 388-408.

———. 1993. Western Forth Valley. In *Quaternary of Scotland.* eds. J. E. Gordon, and D. G. Sutherland, 456-64. London: Chapman & Hall.

Smith, D. E., and R. A. Cullingford. 1981. New evidence for Late Devensian marine limits in east central Scotland - some comments. *Quaternary Newsletter* 35: 12-14.

Smith, D. E., R. A. Cullingford, and C. L. Brooks. 1983. Flandrian relative sea level changes in the Ythan valley, Northeast Scotland. *Earth Surface Processes and Landforms* 8: 423-38.

Smith, D. E., R. A. Cullingford, and W. P. Seymour. 1982. Flandrian relative sea-level changes in the Philorth valley, north-east Scotland. *Transactions of the Institute of British Geographers, New Series* 7: 321-36.

Smith, D. E., A. G. Dawson, R. A. Cullingford, and D. D. Harkness. 1985. The stratigraphy of Flandrian relative sea-level changes at a site in Tayside, Scotland. *Earth Surface Processes and Landforms* 10: 17-25.

Smith, D. E., A. G. Dawson, S. Dawson, C. R. Collins P. Firth, R. A. Cullingford, A. C. de la Vega, C. L. Brooks, S. Charlesworth, S. Duggan, D. Horne, K. Hickey, T. Mighall, S. Pearson, I. S. Stewart, K. Selby, and J. M. Wells. 1995. *Relative Sea Level Changes and Extreme Flooding Events Around European Coasts.* Coventry University: EU Third Framework, Contract Number: EV5V CT93 0266, Final Report.

Smith, D. E., A. G. Dawson, K. R. Hickey, C. R. Firth, C. L. Brooks, S. Dawson, and S. Shi. 1993. Patterns of relative sea-level change during the late Holocene in Scotland. *Climate change, sea level rise and associated impacts in Europe, Final Report, Vol.1, 3-15,* Commission of the European Communities.

Smith, D. E., C. R. Firth, S. C. Turbayne, and C. L. Brooks. 1992. Holocene relative sea-level change and shoreline displacement in the Dornoch Firth area, Scotland. *Proceedings of the Geologists' Association* 103: 237-57.

Smith, D. E., J. Morrison, R. L. Jones, and R. A. Cullingford. 1980. Dating the Main Postglacial Shoreline in the Montrose area, Scotland. In *Timescales in Geomorphology.* eds. R. A. Cullingford, D. A. Davidson, and J. Lewin, 225-45. Chichester: John Wiley.

———. 1980. Dating the Main Postglacial Shoreline in the Montrose area, Scotland. In *Timescales in Geomorphology.* eds. R. A. Cullingford, D. A. Davidson, and J. Lewin, 225-45. Chichester: John Wiley.

Sparks, B. W. 1961. The ecological interpretation of Quaternary non-marine mollusca. *Proceedings of the Linnean Society of London* 172: 71-80.

Steers, J. A. 1973. *The coastline of Scotland.* Cambridge: Cambridge University Press.

Stockmarr, J. 1971. Tablets with spores used in absolute pollen analysis. *Pollen Et Spores* 13: 614-21.

Stoker, M. S., D. Long, and J. A. Fyfe. 1985. A revised Quaternary stratigraphy for the central North Sea. *British Geological Survey Report* 17(2): 35.

Stone, P. 1996. *Geology in south-west Scotland: an excursion guide.* Keyworth, Nottingham: British Geological Survey. pp214.

Streif, H. 1989. Barrier islands, tidal flats, and coastal marshes resulting from a relative rise of sea level in East Frisia on the German North Sea coast. *Proceedings KNGMG Symposium 'Coastal Lowlands, Geology and Geotechnology', 1987.,* 213-23. Dordrecht: Kluwer Academic Publishers.

Stuiver, M., T. F. Braziunas, B. Becker, and B. Kromer. 1991. Climatic, solar, oceanic and geomagnetic influences on Late-Glacial and Holocene atmospheric $^{14}C/^{12}C$ change. *Quaternary Research* 35: 1-24.

Stuiver, M., B. Kromer, B. Becker, and C. W. Ferguson. 1986. Radiocarbon age calibration back to 13,000 years BP and the ^{14}C age matching of the German oak and US bristlecone pine chronologies. *Radiocarbon* 28(2B): 969-79.

Stuiver, M., and G. W. Pearson. 1986. High-precision calibration of the radiocarbon time scale, AD 1950-500 BC. *Radiocarbon* 28(2B): 805-38.

Sutherland, D. G. 1981. *The raised shorelines and deglaciation of the Loch Long/Loch Fyne area western Scotland.* Unpublished PhD Thesis, University of Edinburgh.

———. 1987. Dating and associated methodological problems in the study of Quaternary sea-level changes. In *Sea surface studies.* ed. R. J. N. Devoy, 165-97. Beckenham: Croom Helm.

———. 1991. Late Devensian glacial deposits and glaciation in Scotland and the adjacent offshore region. In *Glacial Deposits in Great Britain and Ireland.* eds. J. Ehlers, P. L. Gibbard, and J. Rose, 53-59. Rotterdam: A. A. Balkema.

———. 1984. The Quaternary deposits and landforms of Scotland and the neighbouring shelves: a review. *Quaternary Science Reviews* 3: 157-254.

Sutherland, D. G., and J. E. Gordon. 1993. The Quaternary in Scotland. In *Quaternary of Scotland.* eds. J. E. Gordon, and D. G Sutherland, 11-45. London: Chapman and Hall.

Sutherland, D. G., and M. J. C. Walker. 1984. A late Devensian ice-free area and possible interglacial site on the Isle of Lewis, Scotland. *Nature* 309: 701-3.

Sylvester-Bradley, P. C., and R. H. Benson. 1971. Terminology for surface features in ornate ostracodes. *Lethaia* 4: 249-86.

Synge, F. M. 1977. Land and sea level changes during the waning of the last regional ice sheet in the vicinity of Inverness. *Inverness Field Club* Special Volume: 83-102.

Tallantire, P. A. 1992. The alder [*Alnus glutinosa* (L.) Gaertn.] problem in the British Isles: a third approach to its palaeohistory. *New Phytologist* 122: 717-31.

Tauber, H. 1965. Differential pollen dispersion and the interpretation of pollen diagrams. *Danmarks Geologiske Undersogelse* 89: 1-69.

———. 1967. Investigations of the mode of pollen transfer in forested areas. *Review of Palaeobotany and Palynology* 3: 277-86.

Taylor, D. M., H. I. Griffiths, H. M. Pedley, and I. Prince. 1994. Radiocarbon-dated Holocene pollen and ostracod sequences from barrage tufa-dammed fluvial systems in the White Peak, Derbyshire, UK. *The Holocene* 4(4): 356-64.

Tebble, N. 1966. *British bivalve seashells.*, 212. Edinburgh: Her Majesty's Stationary Office.

Thomson, M. E., and R. A. Eden. 1977. The Quaternary deposits of the central North Sea, 3. Quaternary sequence in the west central North Sea. *Institute of the Geological Society Report* No. 77/12: 18.

Thorp, P. W. 1987. Late Devensian ice sheet in the western Grampians, Scotland. *Journal of Quaternary Science* 2: 103-12.

Tolonen, K. 1986. Charred particle analysis. In *Handbook of Holocene Palaeoecology and Palaeohydrology*. ed. B. E. Berglund, 485-96. Chichester: John Wiley.

Tooley, M. J. 1978. *Sea-level change in north-west England during the Flandrian stage*. Oxford: Clarendon Press.

Traverse, A., and R. G. Ginsburg. 1966. Palynology of the surface sediments of Great Bahama Bank, as related to water movement and sedimentation. *Marine Geology* 4: 417-59.

Trier, K. 1990. A preliminary study of the brackish and marine Ostracoda of the Pembrokeshire Coast, S.W. Wales. In *Ostracoda and Global Events*. eds. R. C. Whatley, and C. Maybury, 571-81. London: Chapman & Hall.

Troels-Smith, J. 1955. Characterisation of unconsolidated sediments. *Danm. Geol. Unders. IVR* 3 (101): 1-73.

Troels-Smith, J. 1960. Ivy mistletoe and elm: climatic indicators - fodder plants. *Danmarks geologiske undersogelse, IV*, **4**, 1-32.

Underwood, G. J. C. 1994. Seasonal and spatial variation in epipelic diatom assemblages in the Severn estuary. *Diatom Research* 9, no. 2: 451-72.

van de Plassche, O. 1982. *Sea-level change and water level movements in the Netherlands during the Holocene*. Amsterdam: Free University.

Van Harten, D. 1986. Ostracode options in sea-level studies. *Sea-level research: a manual for the collection and evaluation of data*. ed. O. van de Plassche, 435-56. Norwich: Geo Books.

Vogel, J.C., Fuls, A., E. Visser and B. Becker 1993. Pretoria calibration curve for short lived samples. *Radiocarbon* 35(1): 73-86.

von Weymarn, J. 1974. *Coastline development in Lewis and Harris, Outer Hebrides, with particular reference to the effects of glaciation*. Unpublished PhD Thesis, University of Aberdeen.

Vos, P. C., and H. de Wolf. 1988. Methodological aspects of palaeo-ecological diatom research in coastal areas of the Netherlands. *Geologie En Mijnbouw* 67: 31-40.

———. 1993a. Reconstruction of sedimentary environments in Holocene coastal deposits of the southwest Netherlands; the Poortvliet boring, a case study of palaeoenvironmental diatom research. *Hydrobiologia* 269/270: 297-306.

———. 1993b. Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. *Hydrobiologia* 269/270: 285-96.

———. 1994. Palaeoenvironmental research on diatoms in early and middle Holocene deposits in central north Holland (The Netherlands). *Netherlands Journal of Aquatic Ecology* 28(1): 97-115.

Walker, D. 1966. The Late Quaternary History of the Cumberland Lowland. *Philosophical Transactions of the Royal Society, Series B* 251 (770): 1-210.

Walker, M. J. C. 1984. Pollen analysis and Quaternary research in Scotland. *Quaternary Science Reviews* 3: 369-404.

Walker, M. J. C., H. I. Griffiths, V. Ringwood, and J. G. Evans. 1993. An early-Holocene pollen, mollusc and ostracod sequence from lake marl at Llangorse Lake, South Wales, UK. *The Holocene* 3(2): 138-49.

Wall, D. R. 1969. *The taxonomy, and ecology of Recent and Quaternary Ostracoda from the southern part of the Irish Sea.* Unpublished PhD Thesis, University of Wales.

Wang, P., and J. W. Murray. 1983. The use of foraminifera as indicators of tidal effects in estuarine deposits. *Marine Geology* 51: 239-50.

Watson, E. 1977. *Philosophical Transactions of the Royal Society, Series B* 280: 183-98.

West, R. G. 1972. *Pleistocene Geology and Biology.* London: Longman Group Ltd.

West, R. G., B. M. Funnell, and P. E. P. Norton. 1980. An early Pleistocene cold marine episode in the North Sea: pollen and faunal assemblages at Covehithe, Suffolk, England. *Boreas* 9: 1-10.

Whatley, R. C. 1976. Association between podocopid Ostracoda and some animal substrates. *Abh. Verh. Naturwiss. Ver. Hamburg* (NF) 18/19 (Suppl.): 191-200.

———. 1983. Some simple procedures for enhancing the use of ostracoda in Palaeoenvironmental analysis. *N.P.D. Bulletin* 2: 129-46.

Whatley, R. C., and D. R. Wall. 1969. A preliminary account of the ecology and distribution of recent ostracoda in the southern Irish Sea. In *The Taxonomy, Morphology and Ecology of Recent Ostracoda.* ed. J. W. Neale, 268-98. Edinburgh: Oliver & Boyd.

Whittaker, J. E. 1981. The living Ostracoda of Christchurch Harbour, Dorset. In *Microfossils from recent and fossil shelf seas.* eds. J. W. Neale, and M. D. Brasier, 293-303. Ellis Horwood Ltd.

———. 1972. *The taxonomy, ecology and distribution of recent brackish and marine Ostracoda from localities along the coast of Hampshire and Dorset (Christchurch Harbour, The Fleet and Weymouth Bay).* Unpublished PhD Thesis, University of Wales.

Whittington, G., and K. J. Edwards. 1993. Vegetation change on Papa Stour, Shetland, Scotland: a response to coastal evolution and human interference? *The Holocene* 3(1): 54-62.

Wilkinson, M. 1980. Estuarine Benthic Algae and their environment: a review. In *The Shore Environment. Volume 2: Ecosytems.* eds. J. H. Price, D. E. G. Irvine, and W. F. Farnham, 425-86. Academic Press.

Williams, R. 1969. Ecology of the ostracod from selected marine intertidal localities on the coast of Anglesey. In *The Taxonomy, Morphology and Ecology of Recent Ostracoda.* ed. J. W. Neale, 299-329. Edinburgh: Oliver & Boyd.

Wood, A. M. 1996. Pliocene ostracoda of East Anglia (Part I): the Walton Crag at Walton-on-the-Naze, Essex. *Bulletin of the Geological Society of Norfolk* 44: 3-47.

Wood, A. M., and R. C. Whatley. 1994. Northeastern Atlantic and Arctic faunal Provinces based on the distribution of Recent ostracod genera. *The Holocene* 4: 174-92.

Wright, W. B. 1911. On a preglacial shoreline in the Western Isles of Scotland. *Geological Magazine* Decade 5, no. 8: 97-109.

———. 1928. The raised beaches of the British Isles. *1st report of the Commission on Pliocene and Pleistocene Terraces of the International Geographical Union.*

———. 1937. *The Quaternary Ice Age.* 2nd ed. London.

Zong, Y., and M. J. Tooley. 1996. Holocene sea-level changes and crustal movements in Morecambe Bay, northwest England. *Journal of Quaternary Science* 11(1): 43-58.